APPENDIX VI

Modified Swedish Method of Analysis Using Slice Procedure

1. General. The procedures presented in this appendix are for use in making detailed slope stability analyses assuming failure would occur along a circular arc or along a surface of any arbitrary shape. For uniformity and simplicity of presentation, failure is assumed to occur along a trial circular arc. In the modified Swedish method, the sliding mass is divided into slices of either finite or unit width, and a number of trial failure arcs or arbitrary sliding surfaces are investigated to determine which is most critical. An important feature of this method is that earth forces acting on the sides of the slices are considered. The direction of the side forces should be assumed parallel to the average slope of the embankment. Since the side forces are internal forces, they must be balanced to obtain a solution. This requires either the use of analytical procedures using a digital computer to solve a set of simultaneous equations by iteration or the use of graphical procedures involving composite force polygons or graphical integration to balance internal earth forces. The graphical procedures are described in this appendix because of their relative simplicity and clarity. While the modified Swedish method is particularly applicable to homogeneous dams and dikes, it is also used for analyzing zoned embankments. The decision whether to use the modified Swedish method or the wedge method should be based on the stratification or lack of stratification of the soil mass. The circular arcs shown in the examples of this appendix are not necessarily the most critical trial failure surfaces, since the examples have been developed only to illustrate the various methods and procedures.

2. Procedure of Finite Slices. a. Embankment Without Seepage Forces. The sliding mass is divided into a number of slices of convenient width as shown in figure 1 of plate VI-1. Generally, six to twelve slices are sufficient for reasonable accuracy, depending on the embankment zonation and

foundation conditions. A typical slice with forces acting on it is shown in figure 2 of plate VI-1. The force W is the total weight of the slice. The resisting cohesive force C_D is assumed to act parallel to chord AB (fig. 2) and is equal to chord AB times the developed unit cohesion C'_D. The force F_D acting at an angle ϕ_D with the normal to AB is the resultant of the effective normal force at the base and the developed frictional force. Assuming a trial factor of safety, the forces acting on each slice are combined into the composite force polygon shown in figure 3 of plate VI-1, using a convenient force scale and following steps 1 through 5 as outlined below:

(1) Draw the weight vector of the uppermost slice (slice 1).

(2) Draw the developed cohesion vector C_D parallel to the base of the slice.

(3) Draw a line normal to the base of the slice from the upper end of the weight vector.

(4) Construct a line at an angle of ϕ_D from the normal line. This establishes the direction of the vector F_D, the resultant of the normal and frictional forces on the base of the slice.

(5) From the head of the cohesion vector, draw the side earth force vector parallel to the average embankment slope to intersect the resultant vector, thereby closing the force polygon. This establishes the magnitude of the developed vector F_D. The forces on each subsequent slice are then constructed, using the side earth force vector of the previous slice as a base. The composite force polygons must be drawn to a large scale to ensure accurate results, since they are cumulative-type diagrams in which small errors can have a large effect on the error of closure. To obtain the safety factor of balanced external forces, composite force polygons for different trial factors of safety are constructed to determine what safety factor results in closure of the composite force polygon. The errors of closure for each trial composite force polygon are plotted versus the trial factors of safety, as shown in figure 4 of plate VI-1. A smooth curve drawn through the plotted points establishes the factor of safety corresponding to zero error of closure.

b. Sudden Drawdown. Two analyses for each trial failure arc are made for impervious embankments subject to sudden drawdown, one for conditions before drawdown to determine developed normal forces and one after drawdown using the developed normal forces before drawdown. The procedure is illustrated in plate VI-2. A typical slice in an embankment with forces acting before drawdown is shown in figure 1, and corresponding sections of the composite force polygons are shown in figures 2(a) and 2(b) of plate VI-2. In this procedure it is assumed that no seepage has occurred and that the pore pressures acting on the bases of the slices after drawdown reflect the increase in soil weight from submerged to saturated in the drawdown zone. The value of the developed normal force N_D is determined from the before-drawdown analysis and is used in the after-drawdown force polygon, since no increase in developed normal force over the before-drawdown state is considered for an impervious embankment. For any slice with a base located above the upper pool (i.e., the entire slice is composed of material having moist unit weight before and after drawdown), the magnitude of the side earth force determined in the before-drawdown analysis is used in the after-drawdown force polygon. Steps in constructing the composite force polygon before drawdown are the same as those shown in figure 3 of plate VI-1. The magnitude of the developed normal forces is determined from the before-drawdown balanced composite force polygons (zero error of closure) by constructing lines perpendicular to the normal force lines from the tail of the developed friction vectors as shown for one slice in figure 2(a) of plate VI-2. Steps in constructing the after-drawdown force polygon are indicated in figure 2(b). In determining the weight of the slice before drawdown, submerged weights are used for that portion of the slice below the upper pool level. The upper pool level is conservatively assumed to extend horizontally through the embankment to the trial sliding surface. The weight of the slice after drawdown is based on the saturated or moist weight above the upper pool, saturated weight between the upper pool and horizontal extension of the lowered pool, and submerged weight below the lowered pool. When the trial failure surface is a circular arc, the factor of safety after drawdown can be computed as indicated by the equation in plate VI-2. This eliminates the necessity of constructing the after-drawdown composite force polygon in figure 2(b), plate VI-2. The use of a sudden drawdown flow net for semipervious embankment zones and the procedures for this type of analysis are given in plate VI-11.

c. Embankment with Steady Seepage. In the case of steady seepage as shown in figure 1 of plate VI-3, the water forces acting on each slice must be determined. They can be determined from flow nets or assumed to vary linearly below the saturation line. The forces on typical slices are shown in figure 2 of plate VI-3. To simplify construction of the composite force polygon, the resultant R of the weight and water forces for each slice having a sloping water surface is determined, as shown in figure 3 of plate VI-3. The composite force polygon for one trial factor of safety is shown in figure 4 of plate VI-3. The procedure for determining the factor of safety for zero error of closure is the same as that shown in figure 4 of plate VI-1.

d. Earthquake. To consider earthquake effects in a stability analysis, it is assumed that the earthquake imparts an additional horizontal force F_h acting in the direction of potential failure as discussed in paragraph 11f of the main text. This force is computed from the equation

$$F_h = \psi W$$

where

W = weight of sliding mass

ψ = assumed seismic coefficient

The weight W is based on saturated unit weight below the saturation line and moist unit weight above this line, and does not include the weight of any water above the embankment slope. Figure 6 of the main text can be used as a guide in selecting the seismic coefficient. The horizontal force F_h is computed for each slice and included in the force polygon as shown in figure 1(a), plate VI-4. In the case of steady seepage, F_h can be combined with the weight and water forces for each slice as shown in figure 1(b), plate VI-4, and the resultant R can be used in the composite force diagram.

e. Use of Composite Strength Envelopes. Stability analyses for sudden drawdown and steady seepage (including partial pool) require the use of composite strength envelopes. The applicable shear strength depends on the developed normal force, which is influenced by the side earth forces. Consequently, the applicable shear strength must be determined by trial and error as the composite force polygon is constructed. In analysis for sudden drawdown, the S strength is assumed as a basis for ϕ_D and the developed normal force is determined for each slice as the composite force polygon is constructed. The developed normal force N_D divided by ΔL is compared with the normal stress value at the intercept of the S and R envelopes to determine if the R or the S strength governs. For the steady seepage analyses (including partial pool), the developed normal force must also be determined in a manner similar to the procedure illustrated in figure 2(a) of plate VI-2. The S strength is assumed as a basis for ϕ_D in the first portion of the composite force polygon, and the resulting developed normal force divided by ΔL is compared with normal stress at the intercept of the S and R envelopes to determine when the $\frac{R + S}{2}$ strength or the S strength governs. Where the failure arc passes through more than one type of soil, applicable values of shear strength are used for each slice.

3. Graphical Integration Procedure. Graphical integration may be used in stability analyses to balance the internal side earth forces and determine the factor of safety for balanced external forces. Vertical slices of unit width are taken at appropriate intervals along the cross section above the trial failure arc or surface of sliding. Using the trial factor of safety, the resultant of the side earth forces $\Delta E'$ determined from the force polygon for each unit width slice is plotted to form an area diagram. A sufficient number of unit width slices must be used to define accurately the area diagram. $\Delta E'$, which is the resultant of the earth forces acting on the left and right

sides of the unit width slice, is assumed to act parallel to the average embankment slope being analyzed. The trial factor of safety for which the net area of the $\Delta E'$ diagram is zero is the factor of safety for a balance of external forces for the sliding surface being analyzed.

a. Embankment Without Seepage. If the soil mass is not homogeneous with respect to density, the cross section above the arc may be transformed into an equivalent section of uniform density for use in obtaining force polygons (in units of feet) for the unit width slices. This procedure is illustrated in figure 1 of plate VI-5. The height of the equivalent section h' at any point is equal to the height of a unit slice times the ratio of the unit weight of embankment soil in the slice to the unit weight used as a base. Where a slice includes two or more soil types having different unit weights, h' is obtained by adding together the incremental height of each soil type times its unit weight divided by a selected base unit weight γ_{base}. The unit weight of water is often used as the base, but where more convenient the unit weight of one of the soil strata or zones may be used. The force polygon (in units of feet) is constructed for each unit width slice as illustrated in figure 1 of plate VI-5 using the following steps:

(1) Construct h'.

(2) Draw $C'_D = \frac{c}{F.S.} \times \frac{1}{\gamma_{base}} \times \frac{1}{\cos\theta}$ at the base of the width slice h'

(3) Construct a normal line from the head of C'_D.

(4) Construct a resultant friction and normal force vector at an angle of ϕ_D from the normal.

(5) Construct $\Delta E'$ from the top of the unit width slice h' to intersect the friction vector.

(6) The magnitude of F'_D is defined by step 5.

(7) Construct a line from the intersection of F'_D and $\Delta E'$ perpendicular to the normal. This step defines the developed normal force N'_D and $N'_D(\tan\phi_D)$.

The embankment section must be drawn to a large scale so that the force polygons for each unit slice can be constructed accurately. A plot of $\Delta E'$ for each unit slice is then made as shown in figure 2 of plate VI-5. It should be noted that the force polygons for each unit slice are continuous vector plots in either a clockwise or counterclockwise direction so that $\Delta E'$ acts toward the crest in the upper part of the embankment section and toward the toe near the bottom of the embankment section. Consequently, in the area diagram in figure 2 of plate VI-5, minus and plus areas are obtained. When these two areas are equal, the summation of $\Delta E'$ equals zero and the corresponding factor of safety is correct for the sliding surface being analyzed, corresponding to balanced internal forces. It is useful to note that using a lower factor of safety increases the size of the $-\Delta E'$ area and decreases the size of the $+\Delta E'$ area. The areas can be measured, using any arbitrary units, by planimeter or approximated by Simpson's rule. A plot of $\Sigma \Delta E'$, which is the net area of the area diagram, versus trial factors of safety as shown in figure 3 of plate VI-5, can be used to determine the factor of safety for balanced internal forces. The graphical integration procedure requires substantially less time to complete manually than the finite slice procedure (except for the sudden drawdown analysis), and various techniques can be utilized to reduce further the time required. For example, proportional dividers (or a slide rule) can be used when constructing the equivalent section of uniform density shown in figure 1 of plate VI-5. Dividers can be used to transfer $\Delta E'$ vectors to the area diagram.

b. Sudden Drawdown. The use of the graphical integration procedure for sudden drawdown requires two analyses for an impervious embankment, as in the finite slice procedure. The cross section of the embankment above the trial failure arc is transformed into an equivalent section for conditions before drawdown and also for conditions after drawdown as shown in figure 1 of plate VI-6. For conditions before drawdown, moist or saturated unit weights are used above the upper pool level and submerged weights are used below this level. The unit slice force polygon before drawdown is shown in figure 2(a) of plate VI-6. The developed normal stress, using ϕ_D based on the S strength, must be compared with the normal stress at the intersection of the S and R envelopes to determine if the R or S strength governs. The developed normal stress is determined by multiplying the developed normal force for N'_D by γ_{base} $\cos \theta'$. An area diagram and a plot of $\Sigma \Delta E'$ versus trial factors of safety similar to that shown in plate VI-5 are used to determine the factor of safety for balanced side forces. After drawdown, the magnitude of h' is increased to include the weight of water in the embankment between the upper pool and drawdown pool. The values of the developed normal force N'_D found from the condition before drawdown (where $\Sigma \Delta E' = 0$) are used in the unit force polygons for conditions after drawdown as shown in figure 2(b) of plate VI-6. The factor of safety for balanced side forces with $\Sigma \Delta E' = 0$ before drawdown will be greater than the factor of safety for balanced forces with $\Sigma \Delta E' = 0$ after drawdown. Consequently, separate sections and diagrams should be used for the two analyses to minimize possible errors. The above-described procedure must be performed for each trial failure surface investigated. The procedures for this type of analysis are given in plate VI-12.

c. Embankment with Seepage. (1) Water forces on the sides and base of each slice of unit width influence the effective normal force on the base of the slice, as shown in figures 1 and 2 of plate VI-7. The influence of these forces can be accounted for in any appropriate manner, but the following procedure simplifies the computations required. The variation of water pressure with depth is assumed to be the same on both sides of the slice (fig. 1(a)). Therefore, the total forces, U_L and $U_R - U_1$, are equal and opposite and cancel each other. Note that force $U_R - U_1$ applies to that portion of the right side of the slice from the saturation line to a line parallel to it, as shown in figure 1(a), and U_1 applies to the remaining portion of the side of the slice. Although the resultant U of all water forces acting on the slice can be determined from forces U_1 and U_2 alone as shown in figures 1(b), 1(c), and 1(d), it is not necessary to compute these forces separately to determine the resultant force U; however, this can be done if desired.

(2) It can be shown that the resultant force U' (i.e. U/γ_w) acts in a direction perpendicular to the saturation line. This makes it possible to use the simple graphical procedure illustrated in figure 2(a) of plate VI-7 for determining both the magnitude and direction of the resultant force U without determining either U_1 or U_2. The graphical determination of (a) the developed friction force F_D', (b) the developed normal force on the base of the slice N_D', and (c) the resultant side earth force on the slice $\Delta E'$ are illustrated in figure 2(b). This construction is valid only when the unit weight of water is used as the base unit weight in the unit slice procedure. Details required for verifying the validity of this procedure are shown in figure 1 of plate VI-7. The $\Delta E'$ forces are plotted and summed as shown in plate VI-4 to obtain the correct safety factor, which corresponds to $\Sigma\Delta E' = 0$.

(3) In analyses for steady seepage (including partial pool) using the graphical integration procedure, the developed normal force multiplied by $\gamma_w \cos\theta$ must be compared to the normal stress at the intersection of the S and R envelopes to determine when the S and $\frac{R + S}{2}$ strength governs. When the trial sliding surface passes through different materials, the appropriate composite strength envelope should be used for each material.

d. Earthquake. For the earthquake case it is assumed that the earthquake imparts an additional horizontal force F_h acting in the direction of potential failure as discussed in paragraph 11f of the main text and in paragraph 2d. The force F_h should be computed for each unit slice and added to the force polygons of the unit slices as shown in figure 2, plate VI-4. Note that in the equation $F_h = \psi h'(\text{total})$, the term $h'(\text{total})$ is equal to the equivalent height for the total weight of the soil mass in the unit slice based on the saturated unit weight below the water table and moist unit weight above the water table. This equivalent height is not the same as the effective equivalent height $h'(\text{effective})$ based on submerged unit weight below the saturation line and moist unit weight above it.

4. End of Construction--Case I.† Unit weights and shear strengths used in analyzing this condition should correspond to those expected at the end of construction as discussed in paragraph 9 of the main text. Examples of stability analysis for the end of construction condition using the finite slice procedure and the graphical integration procedure are given in plates VI-8 and -9, respectively. Additional analyses should be made during construction using results of field instrumentation measurements and of tests on record samples where high pore water pressures are measured. This is further discussed in Appendix VIII.

5. Sudden Drawdown--Cases II and III. Appropriate unit weights, shear strengths, and design assumptions to be used in sudden drawdown analyses are described in paragraph 11b of the main text. In some extreme cases where a rapid drawdown condition is possible before pore water pressures developed during construction are dissipated, an appropriate reduction in effective stresses should be made using excess pore water pressures expected at the time of rapid drawdown.

a. Finite Slices. (1) Plate VI-10 shows an example of computations for a trial failure arc using slices of finite width for the sudden drawdown case of a homogeneous dam of impervious material. For each trial arc two analyses are required, one to determine the normal forces that develop before drawdown and the second to determine the factor of safety of the slope after drawdown using the normal forces determined in the first analysis. Submerged unit weights below the maximum pool are used for the "before-drawdown" condition; saturated unit weights in the drawdown zone and submerged unit weights below the minimum pool level are used for the "after-drawdown" condition. For the before-drawdown analysis, trial factors of safety are assumed, and errors of closure are determined until a factor of safety for approximate zero closure is found (fig. 3). The force polygon for the zero error of closure is then constructed as shown in figure 4, and the

† Case designations are those described in paragraph 11 of the main test.

normal forces from this force polygon are used for computing the factor of safety for the after-drawdown condition, as shown in tabular form in plate VI-10. The factor of safety after drawdown is determined from the equation shown in plate VI-2.

(2) The effect of seepage forces must be considered in stability analyses of upstream slopes of semipervious soils. In these cases, a drawdown flow net can be used in conjunction with saturated unit weights to determine effective normal stresses and forces as shown in plate VI-11. The water forces on the sides and base of each slice are determined from the flow net. The resultant R of the weight and water forces for each slice (fig. 4, plate VI-11) is used to construct the force polygon (fig. 5). Saturated unit weights are used below the minimum pool level, and it is necessary to consider the water on the outer slopes as part of the slice. In this way, both the weight of water above the slice and the water forces on the sides of the slice can be evaluated. Seepage forces may create a more critical condition near the lowered pool level than is shown by failure arcs through the top of the embankment, and additional analyses for failure arcs emerging part way up the upstream slope may be desirable. Such analyses should consider the riprap as a free-draining material.

b. Graphical Integration Procedure. Plate VI-12 shows computations for a trial failure arc using the graphical integration procedure for the sudden drawdown case of a homogeneous dam of impervious material. Two analyses are required for each trial arc, as in the finite slice procedure. The developed normal forces N_D' for before-drawdown condition are used to construct the after-drawdown force polygons. The factor of safety for the trial arc was determined using the following steps:

(1) Before-Drawdown Analysis. Trial factors of safety were assumed and the net area of the $\Delta E'$ diagram $(\Sigma \Delta E')$ was determined for each trial until a factor of safety for $\Sigma \Delta E' = 0$ was found (fig. 4a, plate VI-12). Shear resistance along the base of each slice of unit width corresponds to the S or R strength, depending on the effective normal stress $(N_D' \cos \theta)$ on the base

of the slice. The shear strength developed along the arc was determined by plotting the developed normal stresses, $N'_D \cos \theta$, determined using the S strength, as shown in figure 2a, plate VI-12. (In this example problem, the S strength was used when the value of $N'_D \cos \theta$ was less than $\frac{4.150 \text{ kips per sq ft}}{0.073 \text{ kips per cu ft}} = 57$ ft.)

(2) Using the factor of safety found in paragraph 5b(1) above for $\Sigma \Delta E' = 0$, corresponding force polygons for before-drawdown conditions were constructed and values of N'_D were determined.

(3) Values of N'_D from paragraph 5b(2) above were then used to construct force polygons for the after-drawdown analysis. The factor of safety for after drawdown was determined by assuming trial factors of safety and determining the net area of the $\Delta E'$ diagram for each trial until a factor of safety for $\Sigma \Delta E' = 0$ was found (fig. 4b, plate VI-12).

6. Partial Pool, Upstream Slope--Case IV. The critical pool elevation is found by determining the critical failure surfaces for various pool levels. If the assumed failure surface is a circular arc, the surface of the pool should intersect the embankment slope directly below the center of the arc for the first trial. The radii of the trial circular arcs are varied until the critical radius is determined. Subsequent trials should be made with the pool above and below this level.

a. Finite Slices. A stability analysis for Case IV using slices of finite width is shown in plate VI-13. Moist weights are used for the materials above pool level and submerged unit weights are used for materials below pool level. A composite of the S and $\frac{R + S}{2}$ design shear strength envelopes is used in computing the shear strength along the assumed failure arc. A number of different pool levels should be analyzed for each trial arc to determine the most critical pool level and factor of safety, and the process repeated for other trial arcs.

b. Graphical Integration Procedure. A stability analysis for Case IV using the graphical integration procedure is illustrated in plate VI-14, using the same section and trial arc as in plate VI-13. In figure 1, the section above the trial arc is converted into an equivalent embankment of uniform density using the submerged weight of the foundation soil as the base unit weight. The correct shear strength used can be determined by plotting values of $N_D' \cos \theta$ as shown in figure 2. There are slight differences in factors of safety between plates VI-13 and -14. These differences are attributed mainly to small differences in measurements of the small-scale diagrams.

7. Steady Seepage, Downstream Slope--Cases V and VI. A simplifying and conservative assumption often made in this analysis is that the curve of piezometric pressures along the failure arc coincides with the saturation line. However, it may be desirable to construct a flow net to determine more closely the piezometric pressures along the failure arc.

a. Finite Slices. A stability analysis for Case V using slices of finite width is shown in plate VI-15. The method of computing the forces on a finite slice is the same as that using water forces as discussed in paragraph 2c of this appendix. In this example, the water forces are assumed to vary linearly below the saturation line. Where a surcharge pool exists above the steady seepage pool (Case VI), the weight of water due to the surcharge pool must be added to those slices upon which it acts. The procedure for determining shear resisting forces using composite strength envelopes is given in paragraph 2e.

b. Graphical Integration Procedure. A stability analysis for Case V using the graphical integration procedure is illustrated in plate VI-16 using the same section and trial arc as in plate VI-15. In figure 1, plate VI-16, the height of the soil above the failure arc is converted into equivalent height of material having a unit weight equal to water for convenience in handling water pressures. Unit width slices are selected at intervals where changes in boundary conditions occur. The slight difference in factors of safety between plates VI-15 and -16 is attributed mainly to small differences in measurements of the small-scale diagrams. In Case VI the equivalent height is increased accordingly for those unit slices that pass through the surcharge pool.

8. Earthquake--Case VII. This case consists of an analysis of Case I, Case IV, or Case V with seismic loadings included. The analysis can be made by using either effective or total stresses, but only total weights are used to compute the earthquake force F_h.

a. Finite Slices. A stability analysis for Case VII using the finite slice method is shown in plate VI-17. In this example, Case V (steady seepage) is analyzed under earthquake conditions. The procedure of analysis is basically the same as that followed in the Case V example in plate VI-15 except that the horizontal earthquake force F_h is added.

b. Graphical Integration. An example analysis for Case VII using the graphical integration method is presented in plate VI-18. In this example, Case I (end of construction) is analyzed with an earthquake loading. The only difference in this example and the example of Case I given in plate VI-9 is that the horizontal earthquake force F'_h is added to the force polygon. Moist and saturated unit weights are used in computing F'_h while moist and submerged unit weights are used in computing the equivalent height h'.

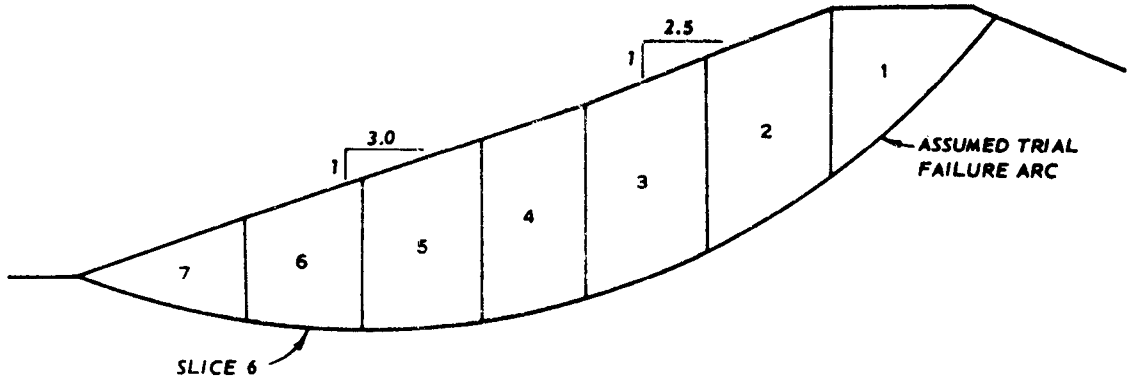
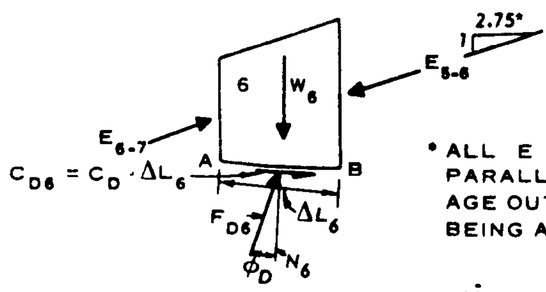


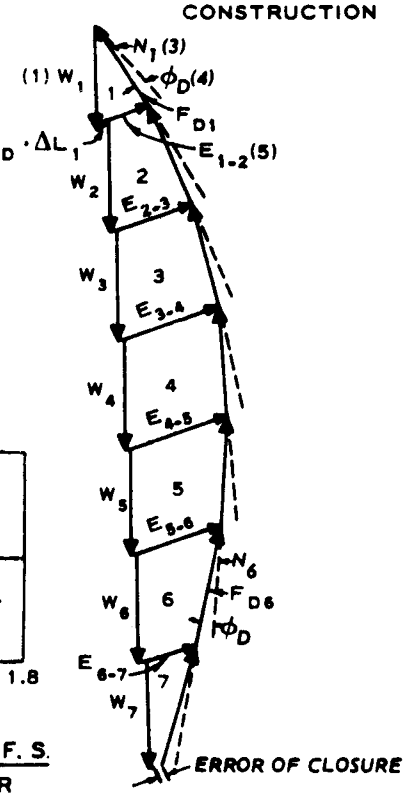
FIGURE 1. EMBANKMENT SECTION



* ALL E FORCES ARE PARALLEL TO AVERAGE OUTER SLOPE BEING ANALYZED.

FIGURE 2. SLICE 6 WITH FORCES

(1) THROUGH (5) ARE STEPS IN CONSTRUCTION



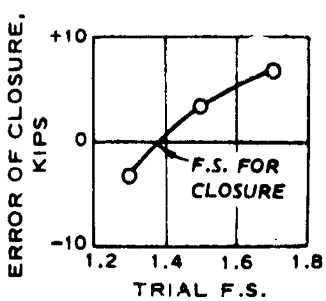


FIGURE 4. TRIAL F. S. VERSUS ERROR OF CLOSURE

FIGURE 3. COMPOSITE FORCE POLYGON FOR ONE TRIAL F. S.

LEGEND

W = WEIGHT OF SLICE

E = EARTH FORCE ON SIDE OF SLICE

N = NORMAL TO BASE OF SLICE

ΔL = LENGTH ACROSS BASE OF SLICE

C_D = DEVELOPED COHESION FORCE

F_D = RESULTANT OF NORMAL AND DEVELOPED FRICTION FORCE

ϕ_D = DEVELOPED ANGLE OF INTERNAL FRICTION OF SOIL

$C_D = \frac{C}{F.S.}$, $\phi_D = \text{ARC TAN} \frac{\text{TAN}\,\phi}{F.S.}$

MODIFIED SWEDISH METHOD
FINITE SLICE PROCEDURE
NO WATER FORCES

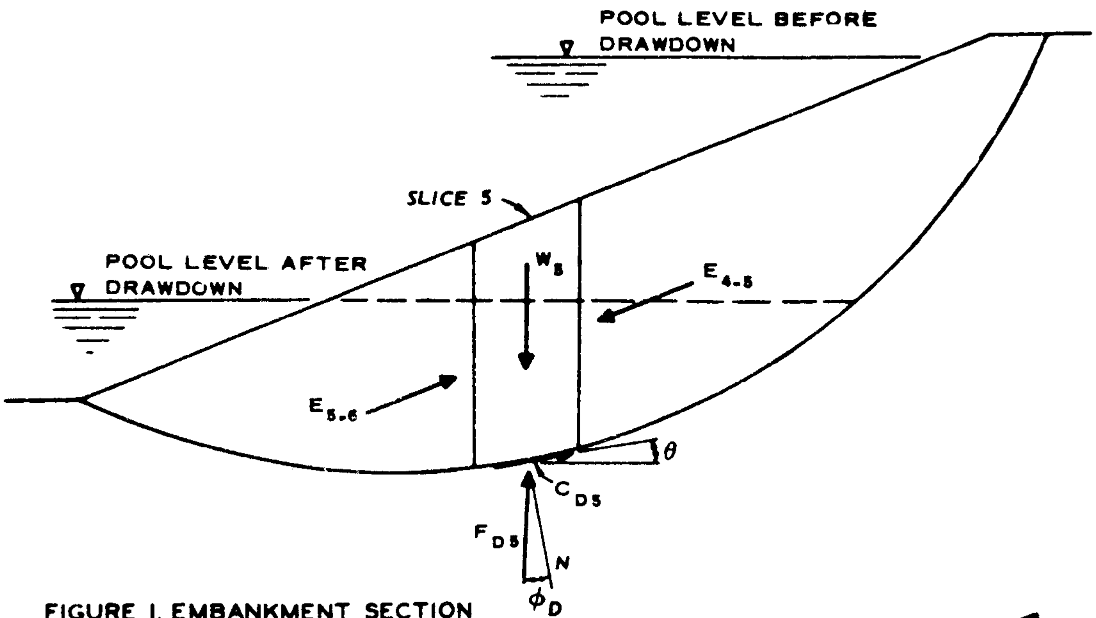
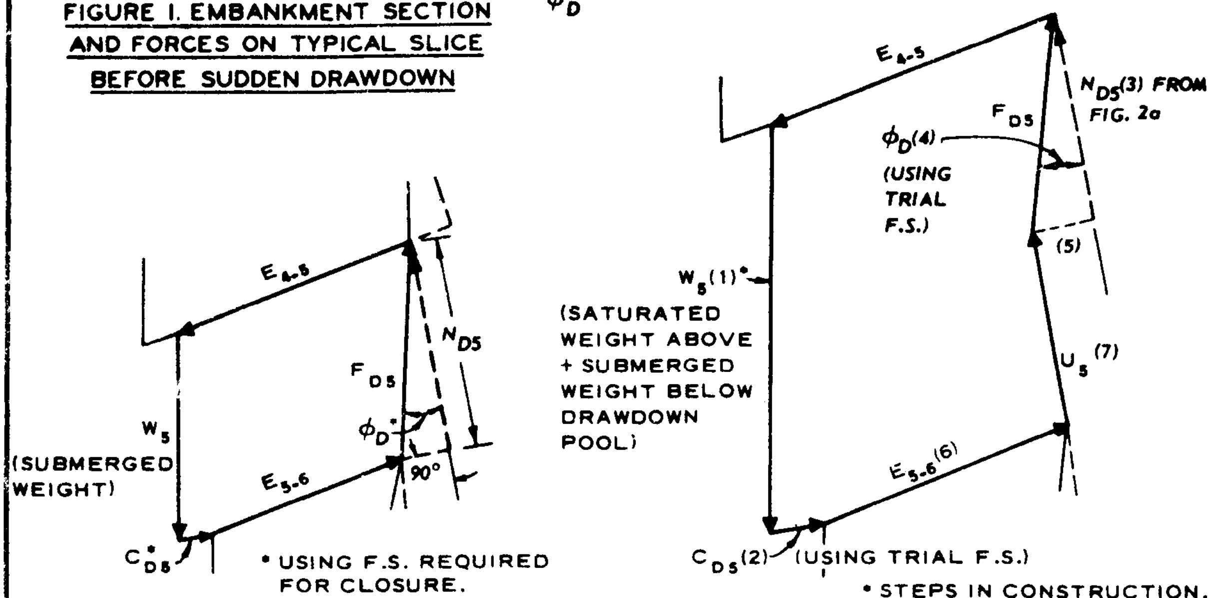


FIGURE I. EMBANKMENT SECTION AND FORCES ON TYPICAL SLICE BEFORE SUDDEN DRAWDOWN



a. BEFORE DRAWDOWN

b. AFTER DRAWDOWN

FIGURE 2. PORTION OF COMPOSITE FORCE POLYGONS

EQUATION FOR F.S. AFTER DRAWDOWN
(ALTERNATIVE PROCEDURE TO 2b)

$$F.S. = \frac{\Sigma N_D \tan \phi + \Sigma C \Delta L}{\Sigma W \sin \theta}$$

N_D = DEVELOPED NORMAL FORCE BEFORE DD
W = WEIGHT OF SLICE AFTER DD
C AND ϕ ARE FOR TOTAL AVAILABLE SHEAR STRENGTH

**MODIFIED SWEDISH METHOD
FINITE SLICE PROCEDURE
SUDDEN DRAWDOWN
IMPERVIOUS EMBANKMENT**

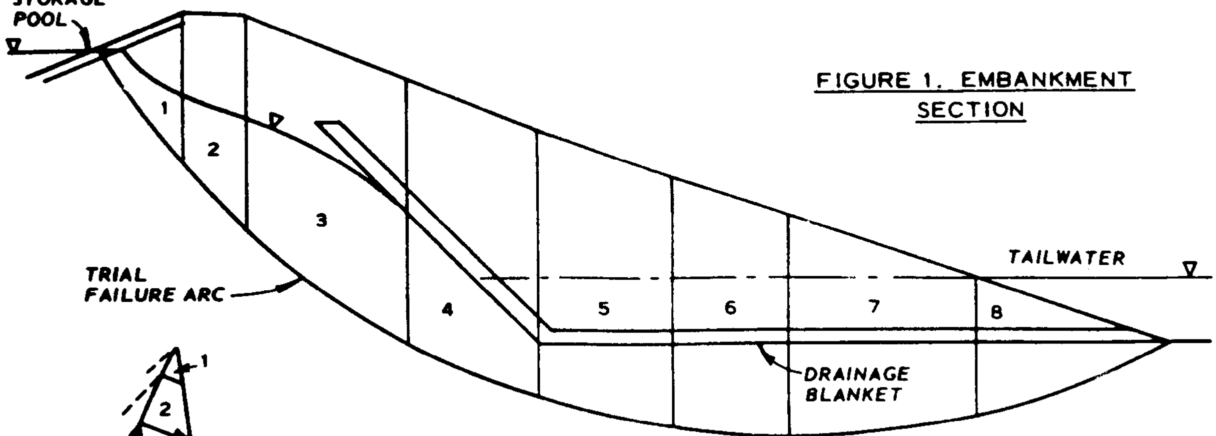
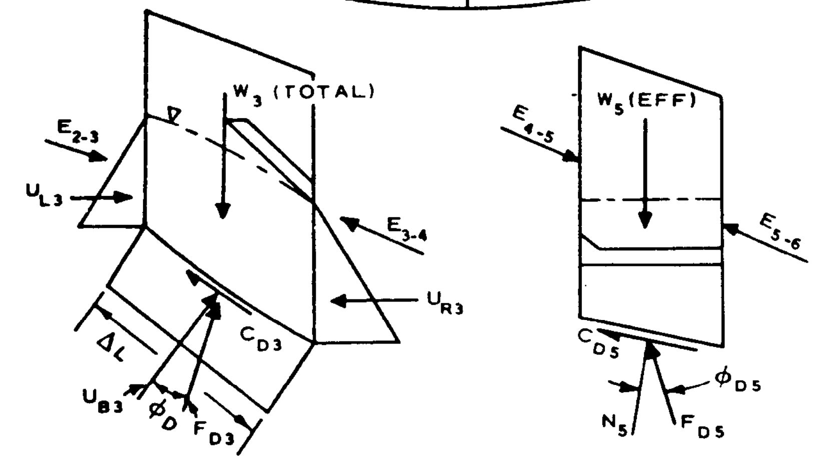


FIGURE 1. EMBANKMENT SECTION



(a) SLICE WITH SLOPING WATER SURFACE

(b) SLICE WITH HORIZONTAL WATER SURFACE

FIGURE 2. FORCES ACTING ON TYPICAL SLICES

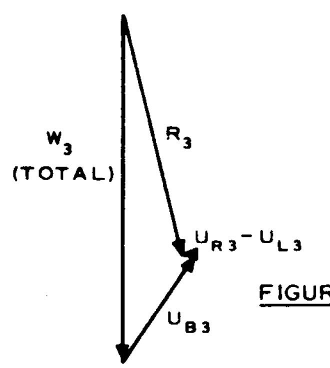


FIGURE 3. RESULTANT OF WEIGHT AND WATER FORCES

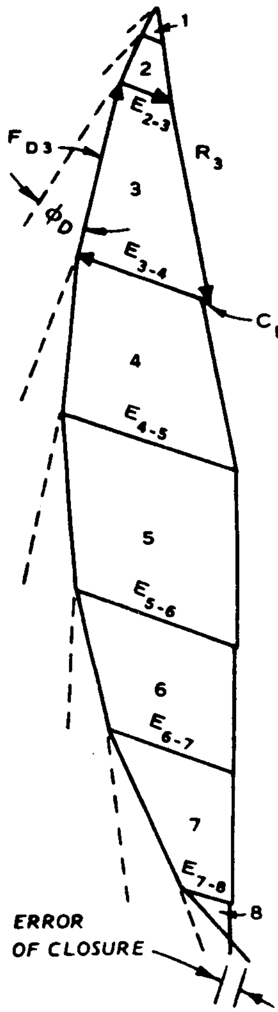


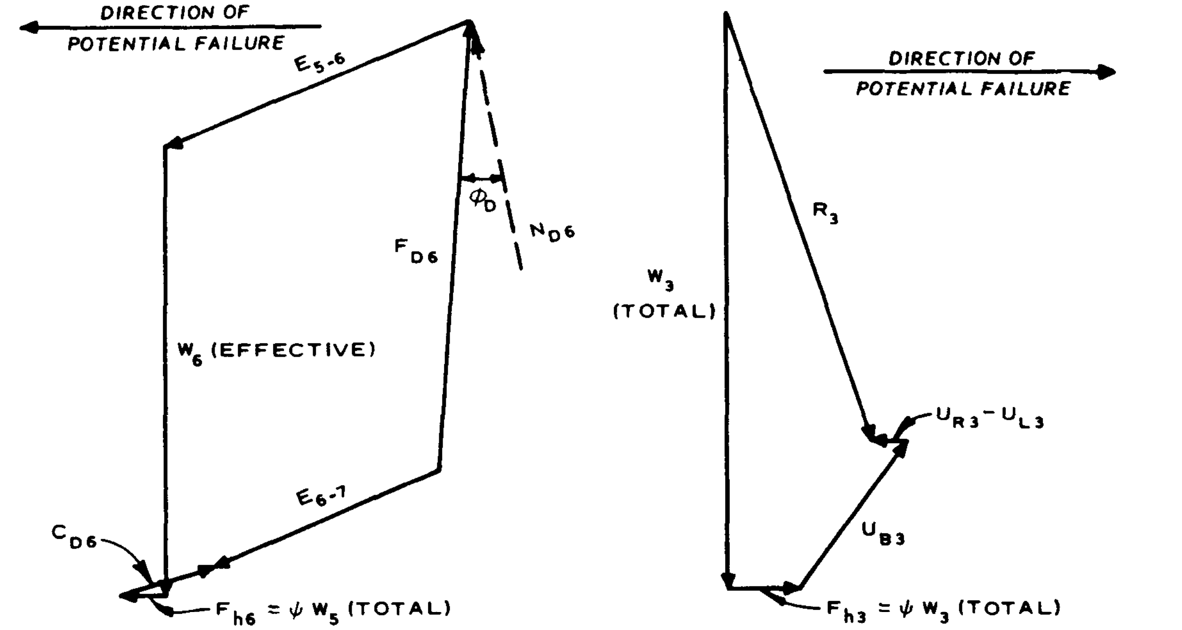
FIGURE 4. COMPOSITE FORCE POLYGON FOR ONE TRIAL F.S.

LEGEND

U_R = WATER FORCE ON RIGHT SIDE OF SLICE
U_L = WATER FORCE ON LEFT SIDE OF SLICE
U_B = WATER FORCE ON BASE OF SLICE

MODIFIED SWEDISH METHOD FINITE SLICE PROCEDURE WITH STEADY SEEPAGE WATER FORCES

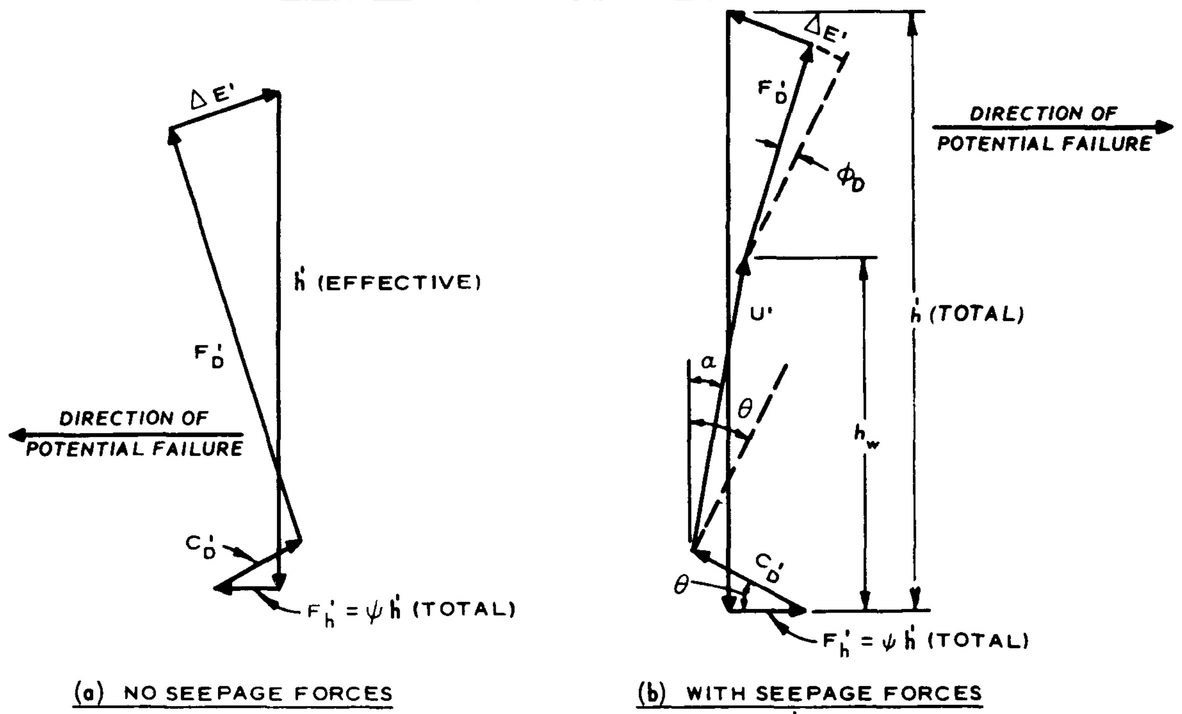
Plate VI-3



(a) NO SEEPAGE FORCES
(SEE FIG. 3, PLATE VI-1)

(b) WITH SEEPAGE FORCES
(SEE FIG. 3, PLATE VI-3)

FIGURE 1. FINITE SLICE PROCEDURE



(a) NO SEEPAGE FORCES
(SEE FIG. 1, PLATE VI-5)

(b) WITH SEEPAGE FORCES
(SEE FIG. 2b, PLATE VI-7)

FIGURE 2. GRAPHICAL INTEGRATION PROCEDURE

MODIFIED SWEDISH METHOD
FINITE SLICE AND GRAPHICAL
INTEGRATION PROCEDURE
EARTHQUAKE LOADING

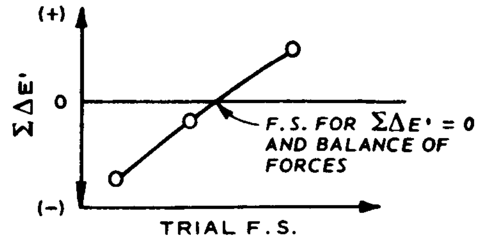


FIGURE 3. $\Sigma\Delta E'$ VERSUS TRIAL F.S.

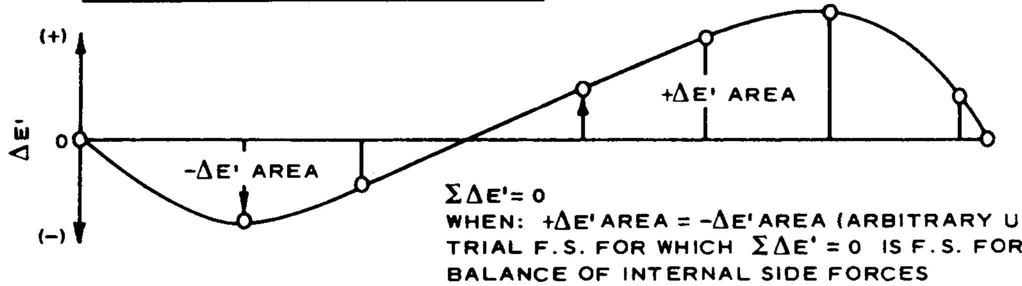


FIGURE 2. $\Delta E'$ AREA DIAGRAM

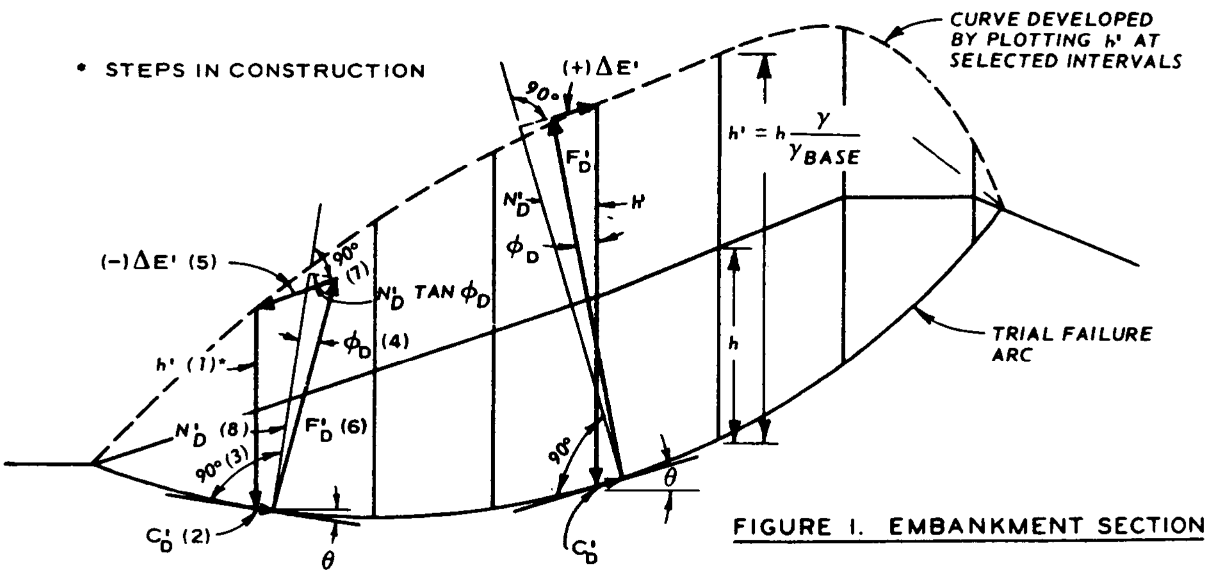


FIGURE 1. EMBANKMENT SECTION

NOTE: ALL COMPONENTS OF UNIT SLICE FORCE POLYGON ARE IN UNITS OF FEET SINCE $h' = h \times \dfrac{\gamma}{\gamma_{BASE}}$

LEGEND

h' = HEIGHT OF UNIT WIDTH SLICE = $h \times \dfrac{\gamma}{\gamma_{BASE}}$

$\Delta E'$ = INCREMENT OF EARTH FORCE REQUIRED TO BALANCE FORCE POLYGON FOR UNIT WIDTH SLICE

C'_D = DEVELOPED COHESION FORCE = $\dfrac{C}{F.S.} \times \dfrac{1}{\gamma_{BASE}} \times \dfrac{1}{\cos\theta}$

N'_D = DEVELOPED NORMAL FORCE

F'_D = RESULTANT OF DEVELOPED NORMAL AND FRICTIONAL FORCES

ϕ_D = DEVELOPED ANGLE OF INTERNAL FRICTION

θ = ANGLE OF INCLINATION OF TRIAL FAILURE ARC WITH HORIZONTAL

MODIFIED SWEDISH METHOD GRAPHICAL INTEGRATION PROCEDURE NO WATER FORCES

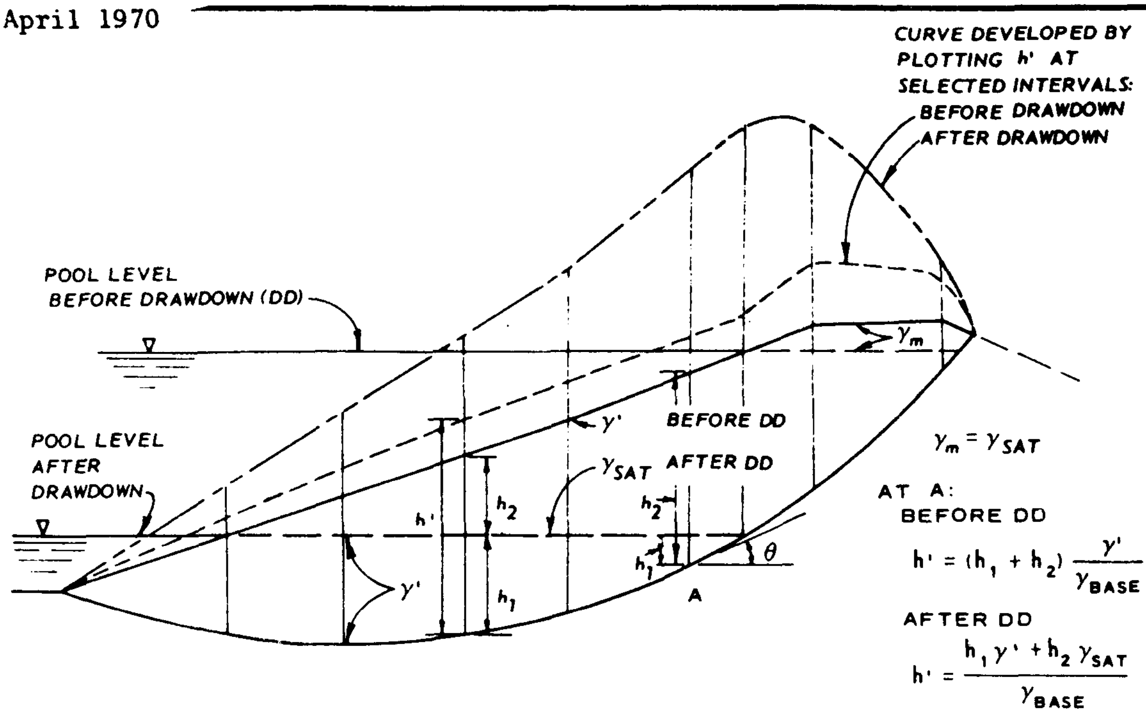
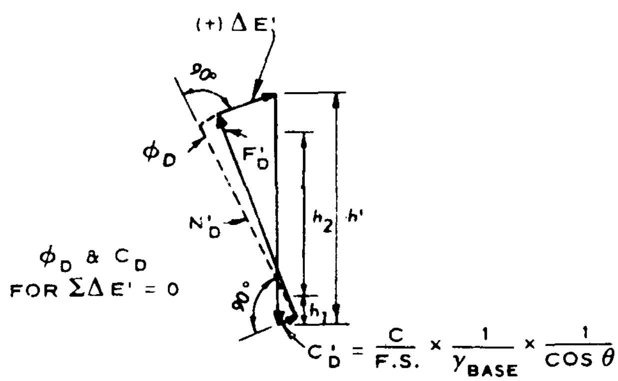
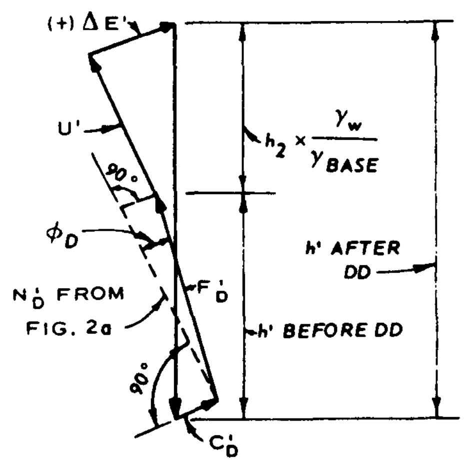


FIGURE 1. EMBANKMENT SECTION



a. BEFORE DRAWDOWN



b. AFTER DRAWDOWN

FIGURE 2. UNIT SLICE FORCE POLYGON AT A

MODIFIED SWEDISH METHOD
GRAPHICAL INTEGRATION
PROCEDURE, SUDDEN DRAWDOWN

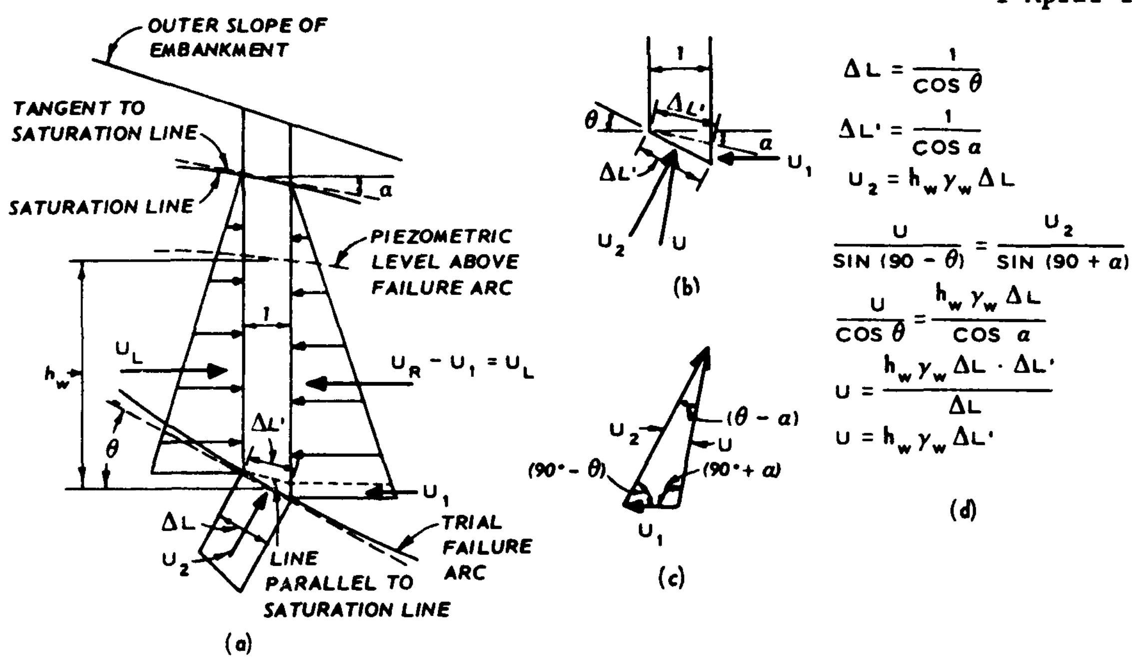


FIGURE 1. RESULTANT U FORCE

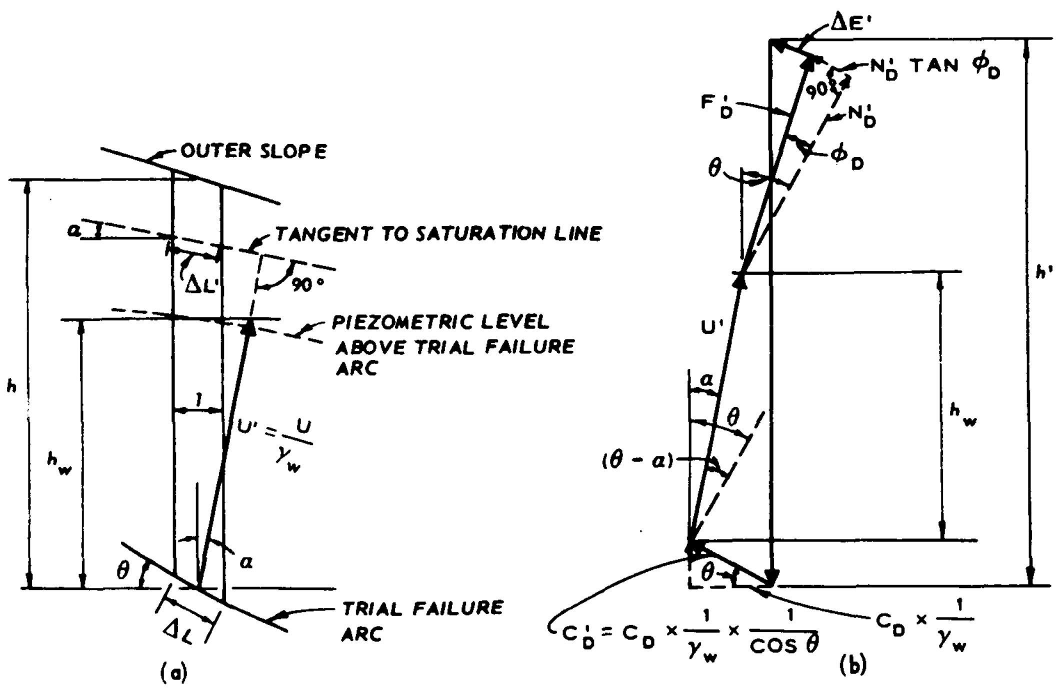


FIGURE 2. GRAPHICAL DETERMINATION OF U' AND N'_D

MODIFIED SWEDISH METHOD
GRAPHICAL INTEGRATION
PROCEDURE, STEADY SEEPAGE
WATER FORCES

SLIDING SURFACE IN	SLICE	HORIZONTAL WIDTH, FT	SLICE HEIGHT, FT LEFT SIDE	SLICE HEIGHT, FT RIGHT SIDE	SLICE HEIGHT, FT AVERAGE	AREA OF SLICE, SQ FT	WEIGHT, KIPS MOIST	WEIGHT, KIPS SUBMERGED	WEIGHT, KIPS TOTAL	BASE LENGTH OF SLICE, ΔL, FT	c ΔL, KIPS	$\frac{c\,\Delta L}{F.S.}$, KIPS*	ϕ_D, DEG*
EMBANKMENT	1	15	23	0	11.5	172.5	23	—	23	23.0	40.9	25.6	3.2
	2	22	44	23	33.5	737.0	100	—	100	31.0	55.2	34.5	
	3	22	61	44	52.5	1155.0	156	—	156	27.5	49.0	30.6	
	4	28	67	61	64.0	1792.0	242	—	242	33.0	58.7	36.7	
	5	28	69	67	68.0	1904.0	257	—	257	31.5	56.1	35.0	
FOUNDATION	6 6'	27	58 9	69 0	63.5 4.5	1714.0 122.0	231 —	— 8	239	29.0	46.4	29.0	1.3
	7 7'	36	47 16	58 9	52.5 12.5	1890.0 450.0	255 —	— 29	284	37.0	59.2	37.0	
	8 8'	40	33 19	47 16	40.0 17.5	1600.0 700.0	216 —	— 46	262	41.0	65.6	41.0	
	9 9'	40	19 16	33 19	26.0 17.5	1040.0 700.0	140 —	— 46	186	41.0	65.6	41.0	
	10 10'	57	0 0	19 16	9.5 8.0	542.0 456.0	73 —	— 30	103	60.0	96.0	60.0	

* FOR F.S. = 1.60

ADOPTED DESIGN DATA					
MATERIAL	Q STRENGTH ϕ DEG	Q STRENGTH TAN ϕ	Q STRENGTH COHESION KIPS/SQ FT	UNIT WT LB/CU FT γ_m	UNIT WT LB/CU FT γ'
EMBANKMENT	5	0.088	1.78	135	—
FOUNDATION	2	0.035	1.60	—	65

FIGURE 2. DESIGN DATA

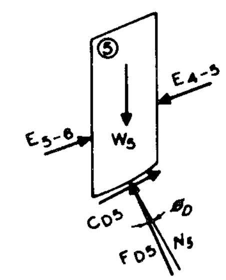


FIGURE 3. TYPICAL SLICE

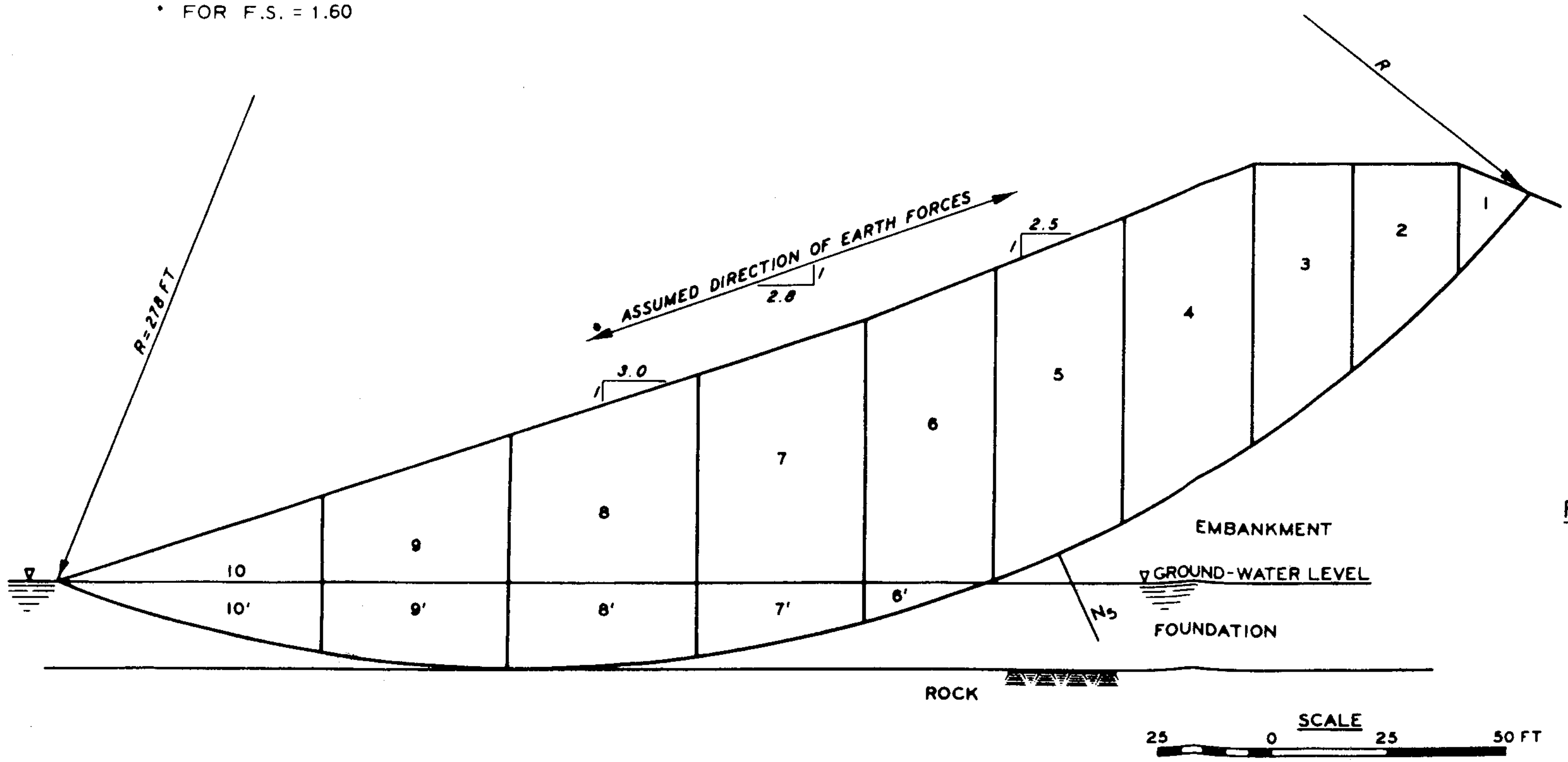


FIGURE 1. EMBANKMENT SECTION

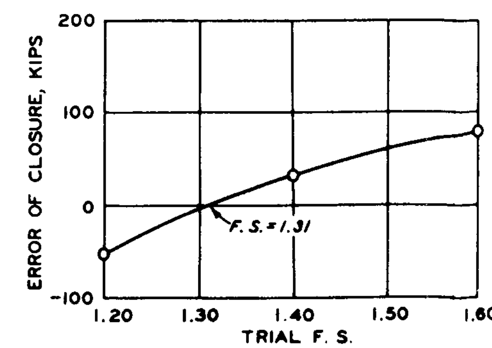


FIGURE 4. TRIAL FACTOR OF SAFETY VERSUS ERROR OF CLOSURE

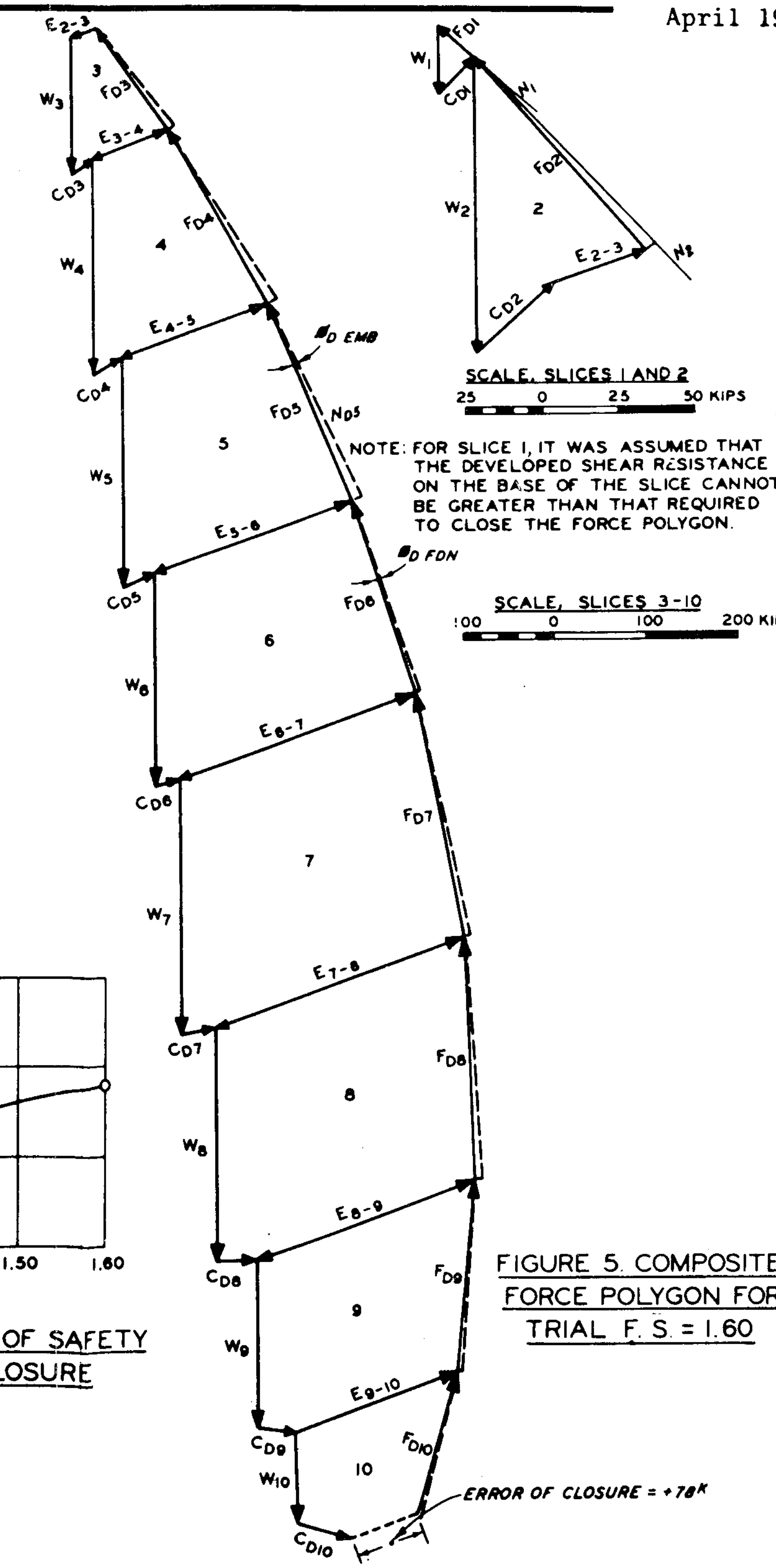


FIGURE 5. COMPOSITE FORCE POLYGON FOR TRIAL F.S. = 1.60

STABILITY ANALYSIS, CASE I - END OF CONSTRUCTION, UPSTREAM SLOPE, MODIFIED SWEDISH METHOD, FINITE SLICE PROCEDURE

ADOPTED DESIGN DATA					
MATERIAL	UNIT WT LB/CU FT		Q STRENGTH		
	γ_m	γ'	ϕ DEG	TAN ϕ	c KIPS/SQ FT
EMBANKMENT	135	–	5	0.088	1.78
FOUNDATION	–	65	2	0.035	1.60

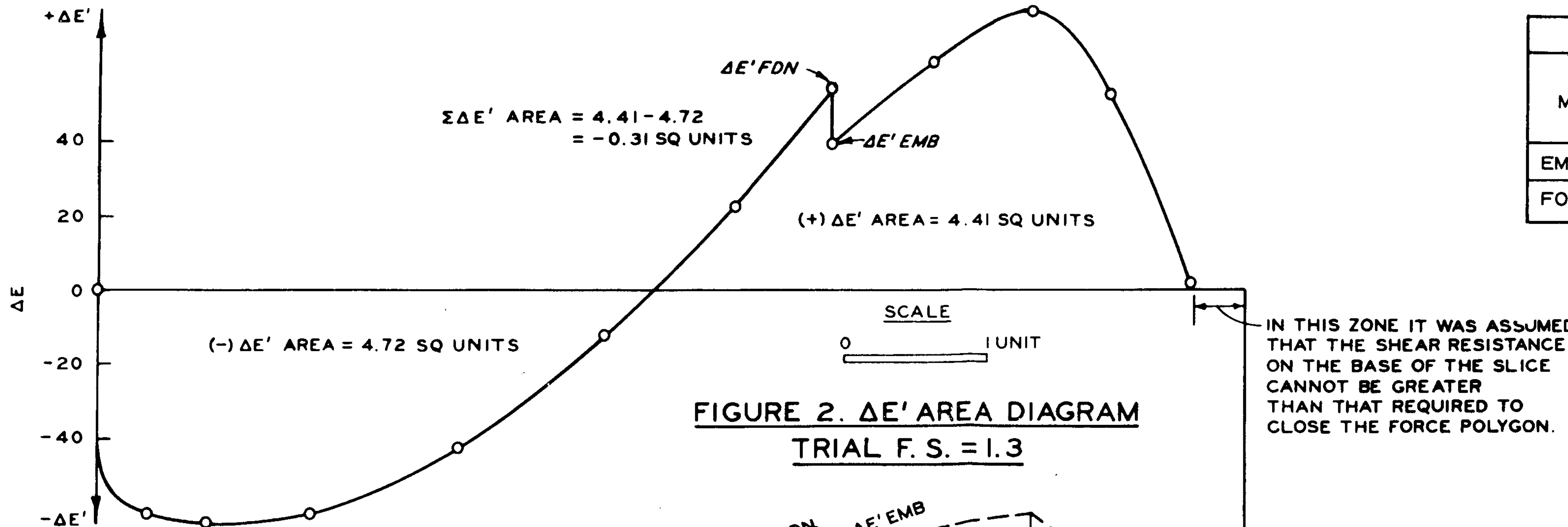


FIGURE 2. ΔE' AREA DIAGRAM
TRIAL F. S. = 1.3

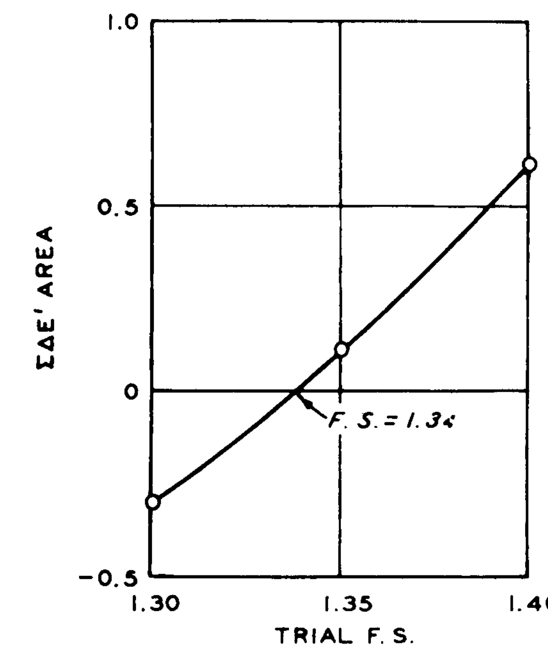
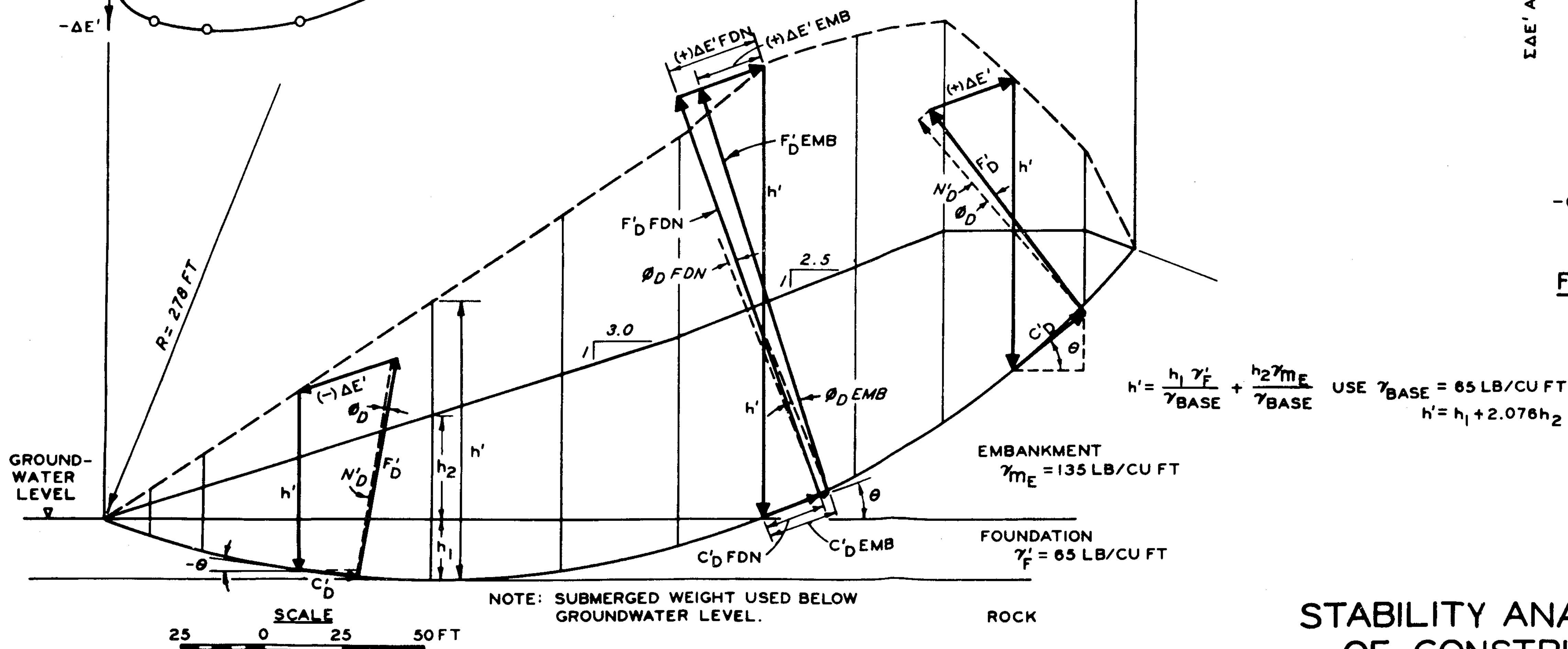


FIGURE 3. TRIAL F. S. VERSUS ΣΔE'



$$h' = \frac{h_1 \gamma'_F}{\gamma_{BASE}} + \frac{h_2 \gamma_{m_E}}{\gamma_{BASE}} \quad \text{USE } \gamma_{BASE} = 65 \text{ LB/CU FT}$$

$$h' = h_1 + 2.076 h_2$$

FIGURE 1. EMBANKMENT SECTION AND UNIT WIDTH SLICE FORCE POLYGONS, TRIAL F. S. = 1.3

STABILITY ANALYSIS, CASE I – END OF CONSTRUCTION, MODIFIED SWEDISH METHOD, GRAPHICAL INTEGRATION PROCEDURE

COMPUTATION OF FACTOR OF SAFETY-SUDDEN DRAWDOWN

$$F.S. = \Sigma \frac{N_D \tan\phi + c\Delta L}{W \sin\theta}$$

WHERE N_D = NORMAL EFFECTIVE FORCE BEFORE DRAWDOWN

W = WEIGHT OF SLICE AFTER DRAWDOWN

SLICE	N_D KIPS	TAN ϕ	N_D TAN ϕ	ΔL FT	$c\Delta L$ KIPS	W KIPS	$\theta°$	SIN θ	W SIN θ KIPS
1	35	—	—	—	—	51.5	56.2	0.831	42.8
2	67	—	—	—	—	118.6	46.7	0.728	86.3
3	64	—	—	—	—	124.6	40.0	0.643	80.1
4	122	—	—	—	—	247.8	32.0	0.530	131.3
Σ 1-4	288	0.577	166.2	—	—	—	—	—	340.5
5	123	—	—	28.0	—	230.7	24.0	0.407	93.9
6	123	—	—	27.0	—	212.9	16.3	0.281	59.8
7	119	—	—	25.4	—	183.8	8.9	0.155	28.5
8	114	—	—	25.0	—	160.7	2.2	0.038	6.1
Σ 5-8	479	0.287	137.5	105.4	126.5	—	—	—	188.3
9	123	—	—	—	—	154.2	-5.0	-0.087	-13.4
10	99	—	—	—	—	103.1	-13.8	-0.239	-24.6
11	45	—	—	—	—	41.7	-23.0	-0.391	-16.3
Σ 9-10	267	0.577	154.1	—	—	—	—	—	-54.3
Σ 1-10	—	—	457.8	—	126.5	—	—	—	474.5

$$F.S. = \frac{457.8 + 126.5}{474.5} = 1.23$$

MEASUREMENTS AND WEIGHTS

SLICE	HORIZONTAL WIDTH, FT	BASE LENGTH OF SLICE, ΔL, FT	SLICE HEIGHT, FT: LEFT SIDE	SLICE HEIGHT, FT: RIGHT SIDE	SLICE HEIGHT, FT: AVERAGE	AREA OF SLICE, SQ FT	WEIGHT, KIPS: SUBMERGED	WEIGHT, KIPS: MOIST OR SATURATED	WEIGHT, KIPS: TOTAL WT BEFORE DRAWDOWN	WEIGHT, KIPS: TOTAL WT AFTER DRAWDOWN
1' 1	20.4 18.6	40.0	6.4 26.9	6.4 0	6.4 13.5	130.6 251.1	— 18.3	17.6 33.9	35.9	51.5
2' 2	20.0	29.0	6.4 48.0	6.4 26.9	6.4 37.5	128.0 750.0	— 54.8	17.3 101.3	72.1	118.6
3' 3	16.0	20.6	0 61.0	6.4 48.0	3.2 54.5	51.2 872.0	— 63.6	6.9 117.7	70.5	124.6
4	28.5	33.5	67.7	61.0	64.4	1835.4	134.0	247.8	134.0	247.8
5 5'	26.0	28.0	57.5 11.5	57.7 0	62.6 5.8	1627.6 150.8	118.8 11.0	219.7 —	129.8	230.7
6 6'	26.0	27.0	47.3 19.0	57.5 11.5	52.4 15.3	1362.4 397.8	99.5 29.0	183.9 —	128.5	212.9
7 7'	25.0	25.4	39.0 23.0	47.3 19.0	43.1 21.0	1077.5 525.0	78.7 38.3	145.5 —	117.0	183.8
8 8'	25.0	25.0	30.7 24.0	39.0 23.0	34.9 23.5	872.5 587.5	63.7 42.9	117.8 —	106.6	160.7
9 9'	30.0	30.2	21.0 21.0	30.7 24.0	25.9 22.5	777.0 675.0	56.7 49.3	104.9 —	106.0	154.2
10 10'	30.0	31.0	11.0 14.0	21.0 21.0	16.0 17.5	480.0 525.0	35.0 38.3	64.8 —	73.3	103.1
11 11'	33.3	36.1	0	11.0 14.0	5.5 7.0	183.2 233.1	13.4 17.0	24.7 —	30.4	41.7

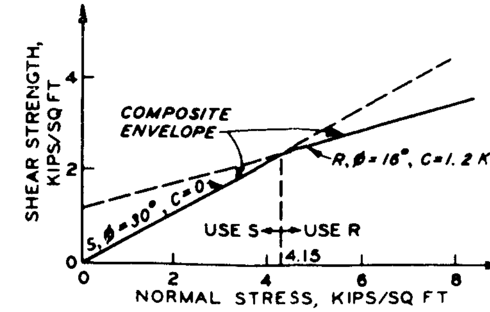


FIGURE 2. COMPOSITE STRENGTH ENVELOPE

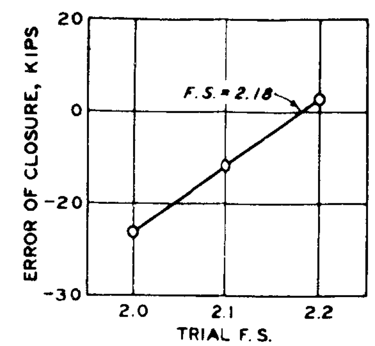


FIGURE 3. TRIAL FACTOR OF SAFETY VERSUS ERROR OF CLOSURE (BEFORE DRAWDOWN)

NOTE FOR FIG. 4:
THE SHEAR STRENGTH USED FOR EACH SLICE IN THE FORCE POLYGON IS SELECTED BY TRIAL. WHEN THE NORMAL FORCE N_D DETERMINED USING THE S STRENGTH EXCEEDS 4.15 KIPS/SQ FT TIMES THE BASE LENGTH OF THE SLICE, THE R STRENGTH IS USED FOR THAT SLICE. THIS WAS THE CASE FOR SLICES 5, 6, 7, AND 8.

FOR F.S. = 2.18:

	S	R
TAN Φ_D	0.265	0.131
Φ_D, DEG	14.8	7.5
C_D, KIPS/SQ FT	0	0.55

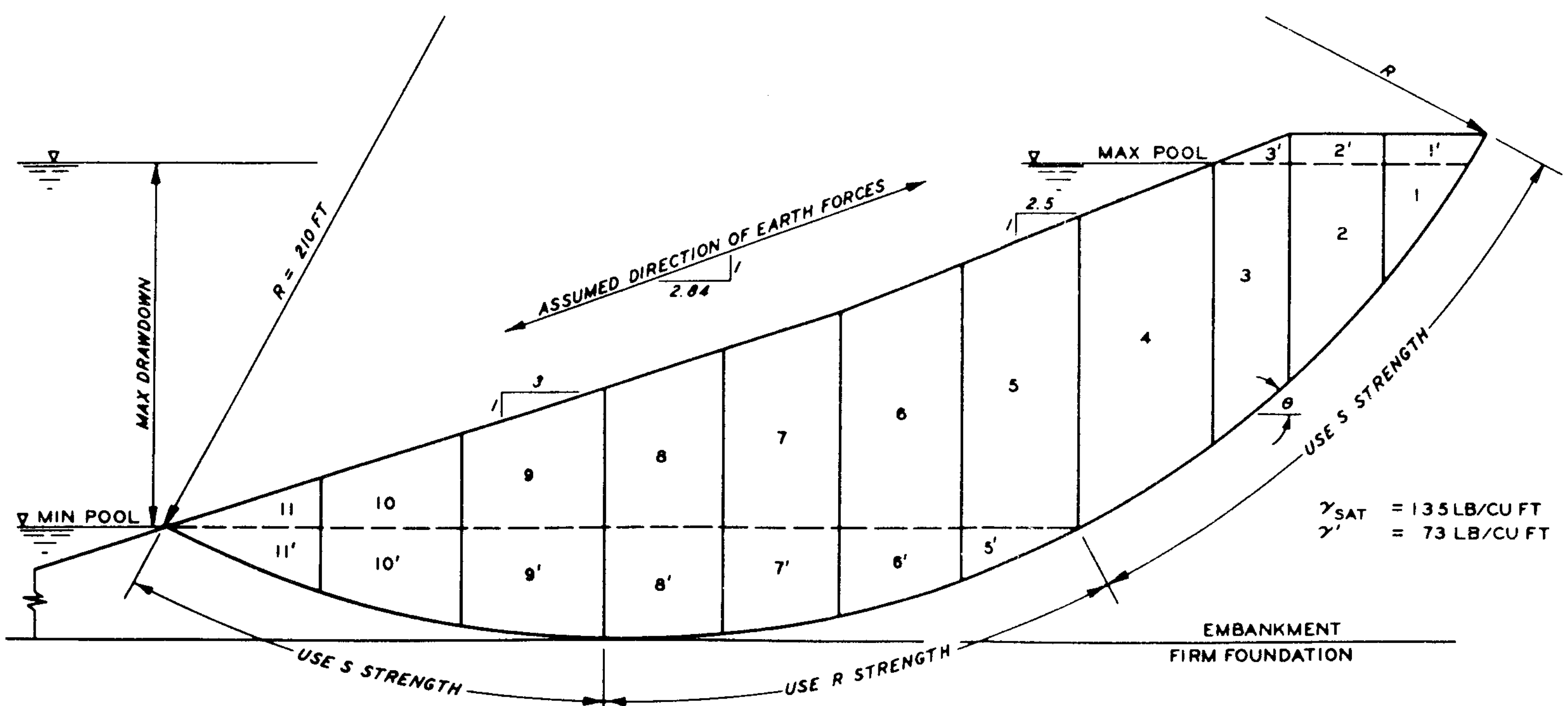


FIGURE 1. EMBANKMENT SECTION

SCALE
25 0 25 50 FT

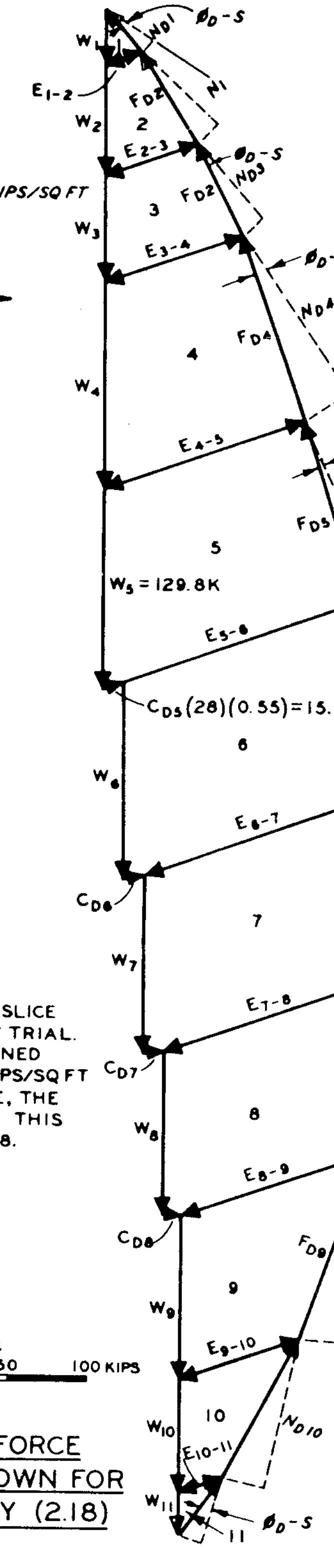


FIGURE 4. COMPOSITE FORCE POLYGON BEFORE DRAWDOWN FOR TRUE FACTOR OF SAFETY (2.18)

STABILITY ANALYSIS, CASE II — SUDDEN DRAWDOWN, UPSTREAM SLOPE, MODIFIED SWEDISH METHOD, FINITE SLICE PROCEDURE

SLICE	HORIZONTAL WIDTH, FT	BASE LENGTH OF SLICE, ΔL, FT	SLICE HEIGHT, FT: LEFT SIDE	SLICE HEIGHT, FT: RIGHT SIDE	SLICE HEIGHT, FT: AVERAGE	AREA OF SLICE, SQ FT	WEIGHT OF SLICE, KIPS(1)	WATER PRESSURE ON FAILURE ARC, KIPS/SQ FT (2): LEFT	WATER PRESSURE ON FAILURE ARC, KIPS/SQ FT (2): RIGHT	U_L, KIPS(3)	U_R, KIPS(3)	$(U_L - U_R)$, KIPS	UPLIFT (U_B), KIPS(4)
1	25	42.0	23.5	0	11.75	293.8	41.1	0.88	0	10.3	0	10.3	18.5
2	35	49.0	44.0	23.5	33.75	1181.0	165.3	2.06	0.88	45.3	10.3	35.0	72.0
3	40	50.0	58.0	44.0	51.00	2040.0	285.6	3.15	2.06	91.4	45.3	46.1	130.2
4	40	45.5	66.0	58.0	62.00	2480.0	347.2	3.88	3.15	128.0	91.4	36.6	160.0
5	40	43.0	68.0	66.0	67.00	2680.0	375.2	4.12	3.88	140.0	128.0	12.0	172.0
6	40	41.5	65.0	68.0	66.50	2660.0	372.4	4.09	4.12	132.9	140.0	-7.1	170.4
7	50	50.0	55.5	65.0	60.25	3012.0	421.7	3.50	4.09	97.1	132.9	-35.8	189.7
8	55	55.0	36.5	55.5	46.00	2530.0	354.2	2.44	3.50	44.5	97.1	-52.6	163.4
9 9'	70	72.0	0 20.0	36.5 0	18.25 10.00	1278.0 700.0	178.8 43.8	1.25	2.44	12.5	44.5	-32.0	132.8

(1) SLICE 9': MULTIPLY AREA BY γ_w TO DETERMINE WEIGHT. ALL OTHER SLICES, MULTIPLY AREA BY γ_{SAT} TO DETERMINE WEIGHT.
(2) PIEZOMETRIC HEAD AT BASE × γ_w.
(3) PIEZOMETRIC PRESSURE AT BASE × SLICE HEIGHT ÷ 2.
(4) BASE LENGTH OF SLICE × AVERAGE PIEZOMETRIC PRESSURE ON BASE.

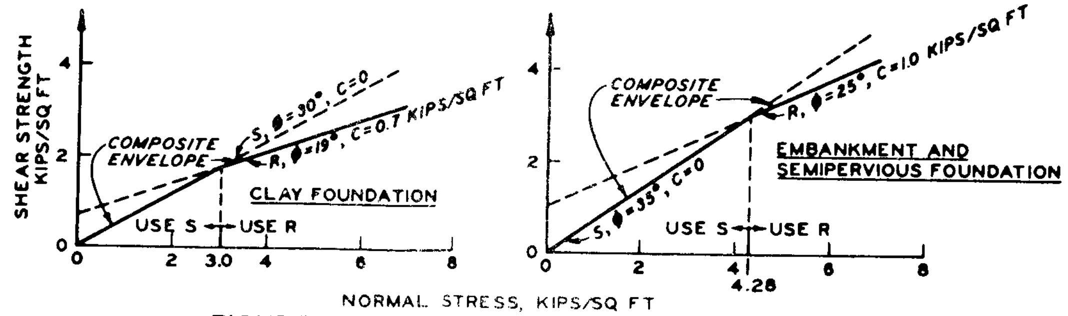


FIGURE 2. COMPOSITE STRENGTH ENVELOPES

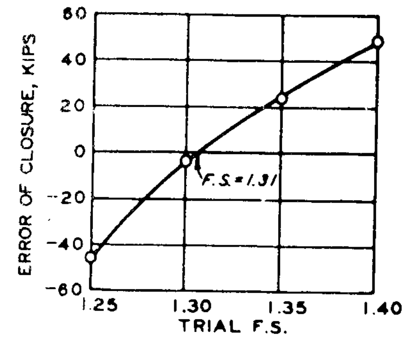


FIGURE 3. TRIAL FACTOR OF SAFETY VS ERROR OF CLOSURE

ADOPTED DESIGN DATA						
MATERIAL	TAN φ		COHESION KIPS/SQ FT		UNIT WT LB/SQ FT	
	R	S	R	S	γ_{SAT}	γ'
FOUNDATION CLAY	0.344	0.577	0.7	0	*	*
SEMIPERVIOUS FOUNDATION AND EMBANKMENT	0.466	0.700	1.0	0	140	78

* ASSUMED SAME AS SEMIPERVIOUS MATERIAL.

NOTES FOR FIGURE 5:
THE SHEAR STRENGTH USED FOR EACH SLICE IN THE FORCE POLYGON IS SELECTED BY TRIAL. WHEN THE NORMAL FORCE N_D (DETERMINED USING THE S STRENGTH) DIVIDED BY THE BASE LENGTH OF THE SLICE EXCEEDS 4.28 KIPS/SQ FT IN SEMIPERVIOUS MATERIAL OR 3.0 KIPS/SQ FT IN THE FOUNDATION CLAY, THE R STRENGTH IS USED FOR THAT SLICE.

FOR TRIAL F.S.=1.30:

	CLAY FOUNDATION S_F	CLAY FOUNDATION R_F	SEMIPERVIOUS S_P	SEMIPERVIOUS R_P
TAN Φ_D	0.444	0.265	0.538	0.358
Φ_D, DEG	24.0	14.8	28.3	19.7
C_D, KIPS/SQ FT	0	0.538	0	0.769

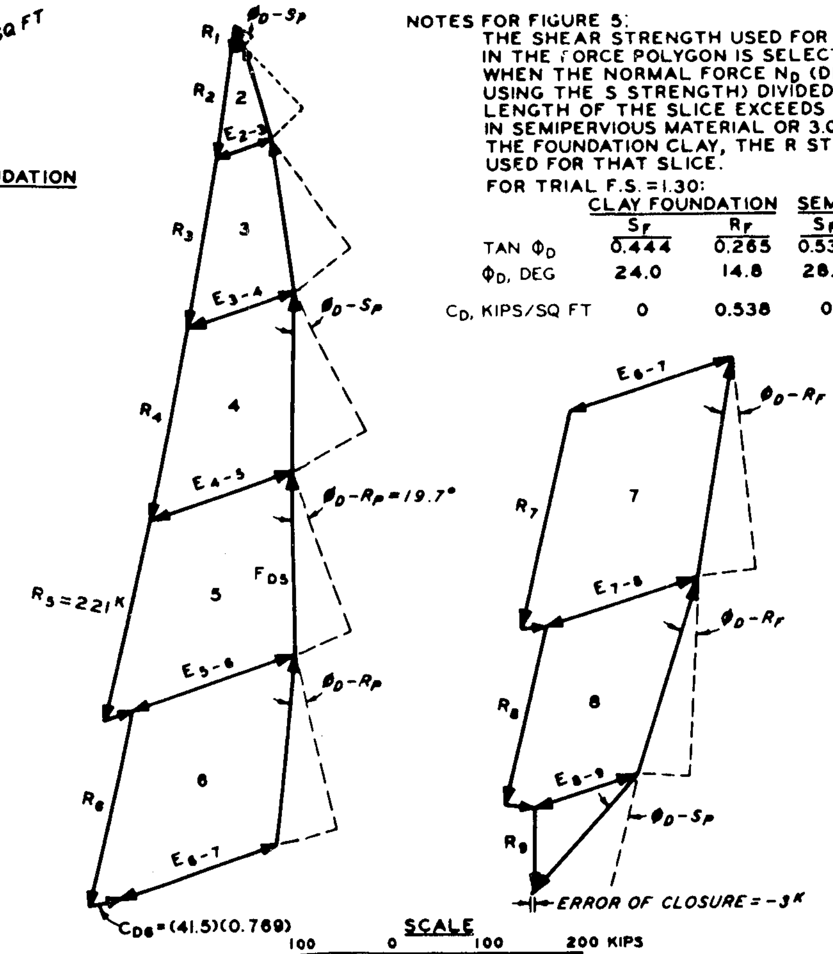


FIGURE 5. COMPOSITE FORCE POLYGON, TRIAL F.S.=1.30

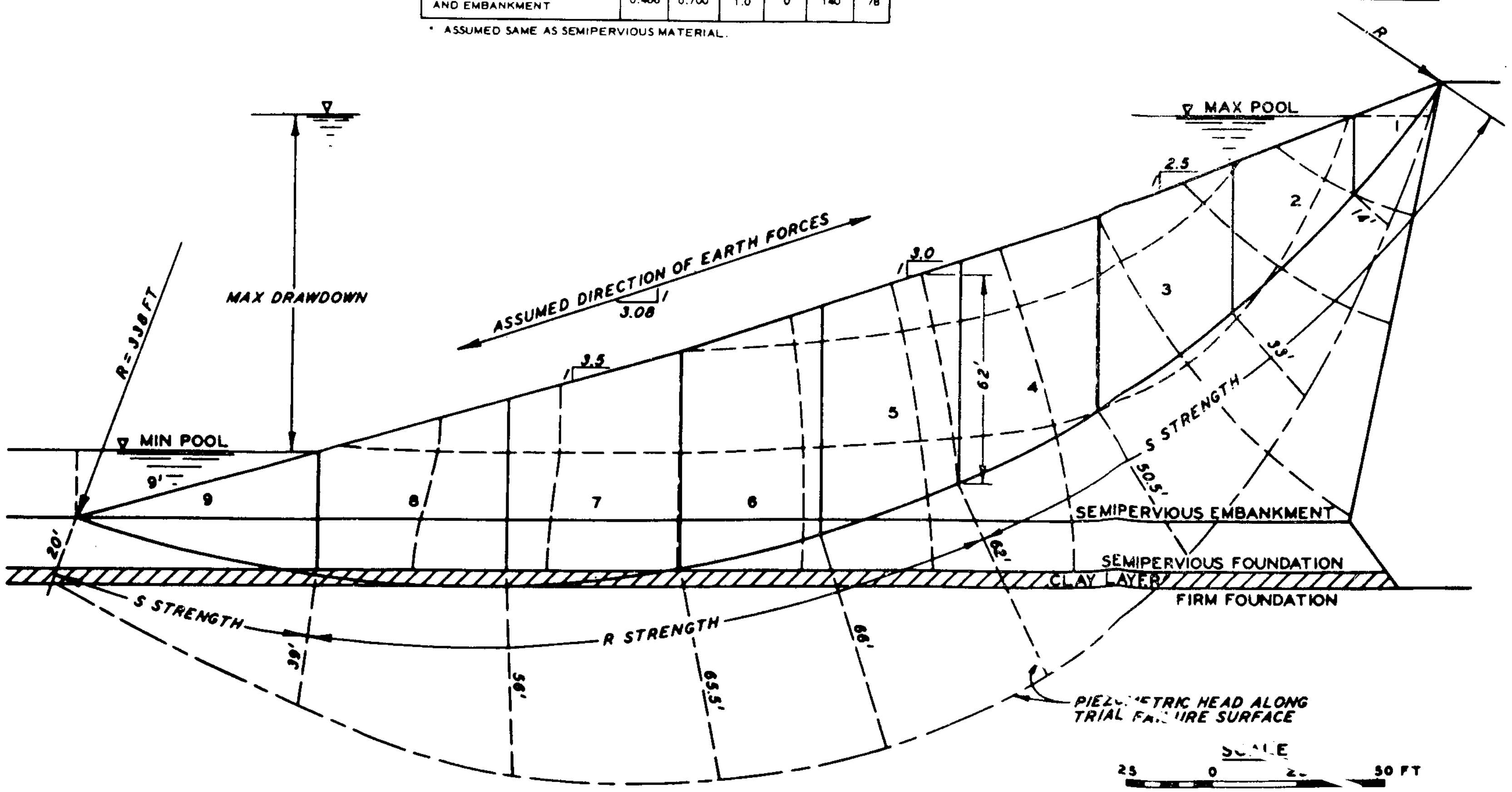


FIGURE 1. EMBANKMENT SECTION

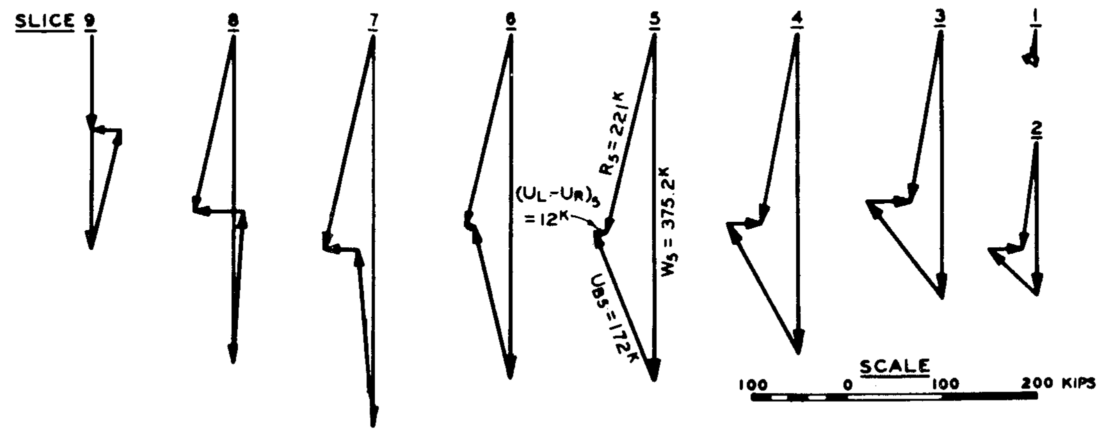


FIGURE 4. RESULTANT OF WEIGHT AND WATER FORCES ON SLICE

STABILITY ANALYSIS, EMBANKMENT WITH CENTRAL CORE AND SEMIPERVIOUS SHELL, CASE II - SUDDEN DRAWDOWN, MODIFIED SWEDISH METHOD, FINITE SLICE PROCEDURE

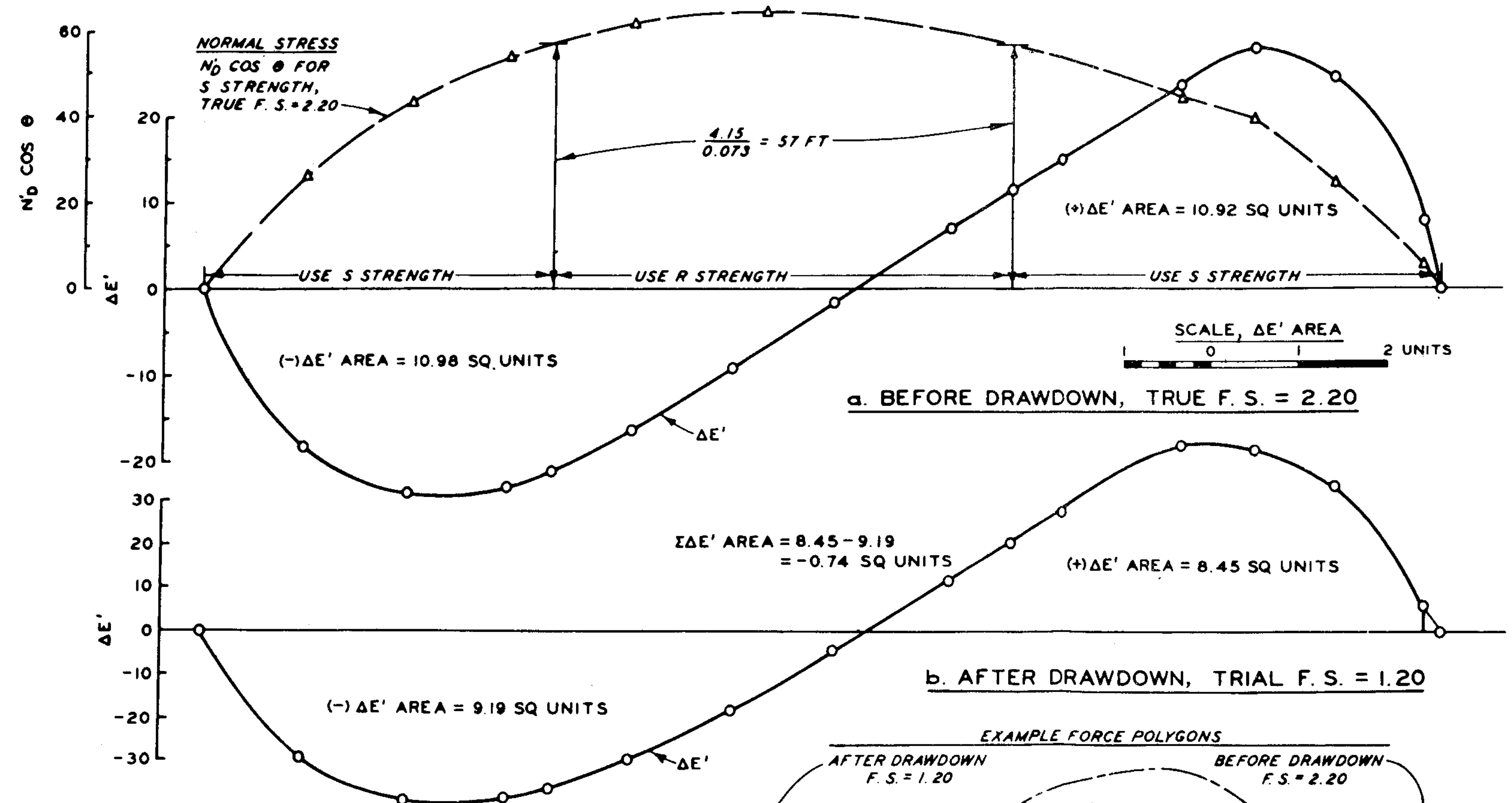


FIGURE 2. ΔE' AREA DIAGRAM

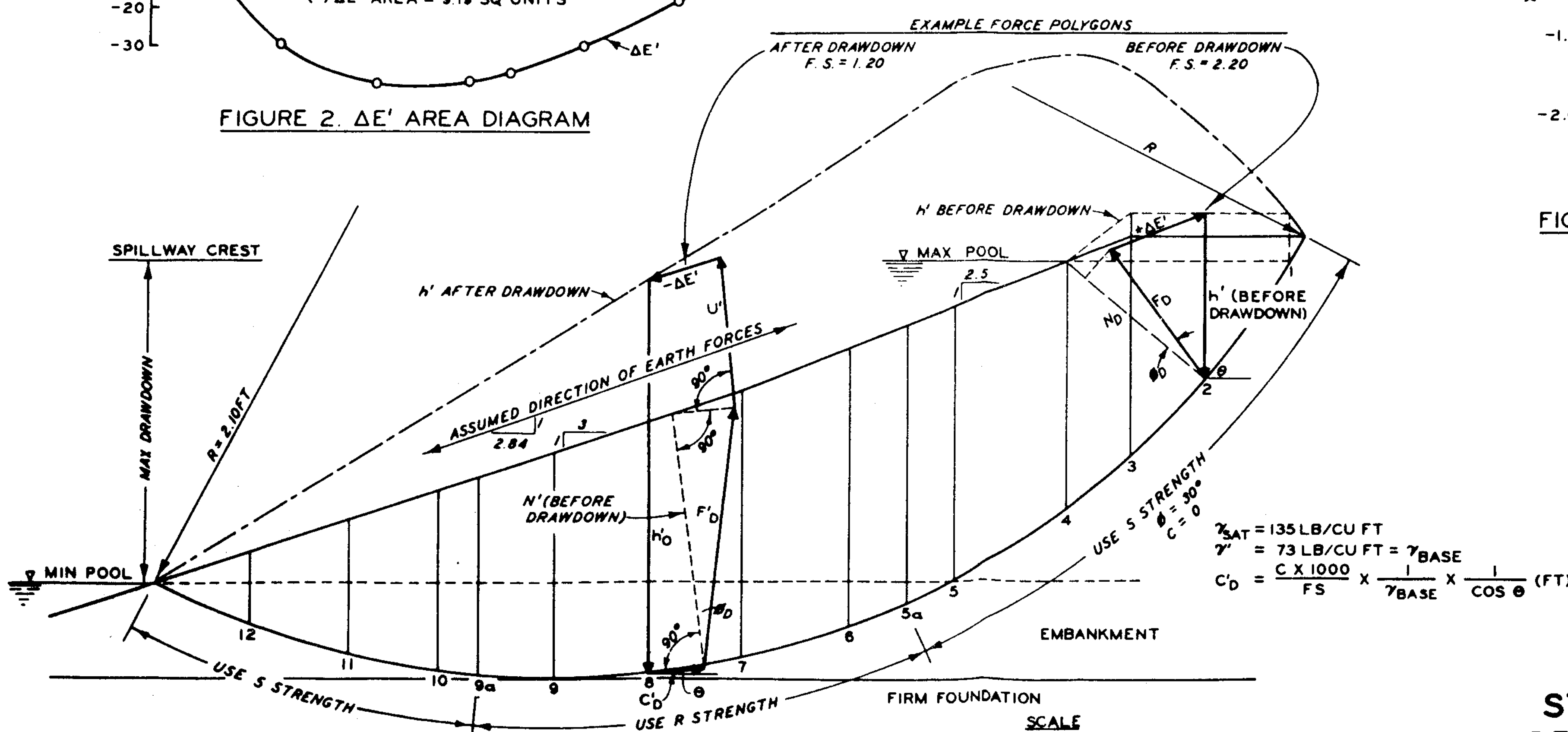


FIGURE 1. EMBANKMENT SECTION AND UNIT WIDTH SLICE FORCE POLYGON,
TRIAL F. S.: BEFORE DRAWDOWN = 2.20, AFTER DRAWDOWN = 1.20

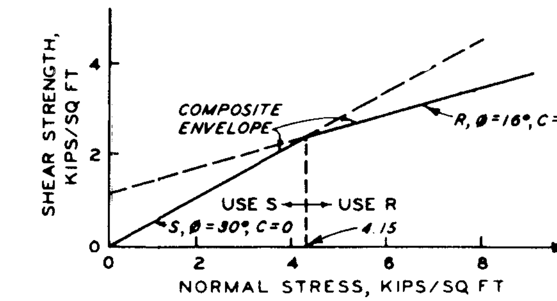
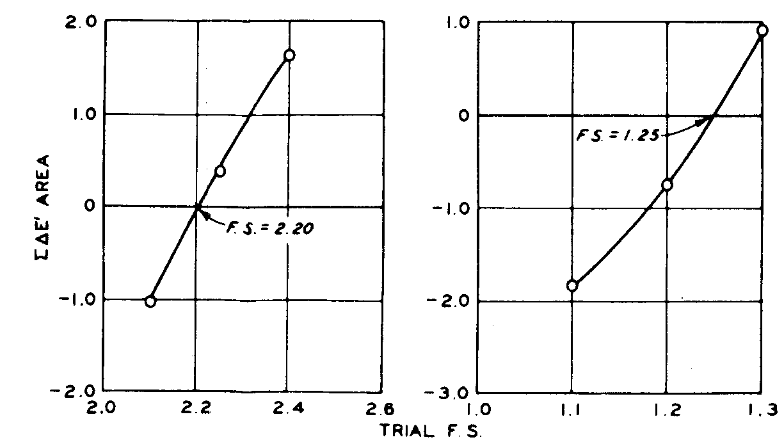


FIGURE 3. COMPOSITE STRENGTH ENVELOPE



a. BEFORE DRAWDOWN
b. AFTER DRAWDOWN
FIGURE 4. TRIAL FACTOR SAFETY VERSUS ΣΔE'

STABILITY ANALYSIS, CASE II - SUDDEN DRAWDOWN, UPSTREAM SLOPE, MODIFIED SWEDISH METHOD, GRAPHICAL INTEGRATION PROCEDURE

SLICE	HORIZONTAL WIDTH, FT	BASE LENGTH OF SLICE, ΔL, FT	SLICE HEIGHT, FT: LEFT SIDE	SLICE HEIGHT, FT: RIGHT SIDE	SLICE HEIGHT, FT: AVERAGE	AREA OF SLICE, SQ FT	WEIGHT, KIPS: MOIST	WEIGHT, KIPS: SUBMERGED	WEIGHT, KIPS: TOTAL
1	13 3	24 9	21 0	0	10 5	140 0	18 0	—	18.0
2	18 0	28 0	34 5	21 0	27 8	500 0	65 0	—	65 0
3	15 0	20 0	28 0	34 5	31 3	470 0	61 0	—	68.0
3'			13 5	0	6 7	100 5	—	7 0	
4	24 0	28 7	18 5	28 0	23 3	564 0	73 0	—	108.0
4'			29 5	13 5	21 5	515 0	—	35 0	
5	28 0	31 5	9 0	18 5	13 8	386 0	50 0	—	117.0
5'			29 5	29 5	29 5	825 0	—	56 0	
5''			12 5	0	6 3	176 0	—	11 0	
6	30 0	31 0	0	9 0	4 5	135 0	18 0	—	109.0
6'			29 5	29 5	29 5	885 0	—	60 0	
6''			20 0	12 5	16 3	489 0	—	31 0	
7'	30 0	30 5	22 0	29 5	25 8	774 0	—	53 0	93 0
7''			22 6	20 0	21 3	639 0	—	40 0	
8'	25 0	25 2	15 5	22 0	18 8	470 0	—	32 0	66.0
8''			21 0	22 6	21 8	545 0	—	34 0	
9'	31 0	32 0	8 0	15 5	11 8	366 0	—	25 0	59.0
9''			14 0	21 0	17 5	542 0	—	34 0	
10'	32 0	34 3	0	8 0	4 0	128 0	—	9 0	23.0
10''				14 0	7 0	224.0	—	14 0	

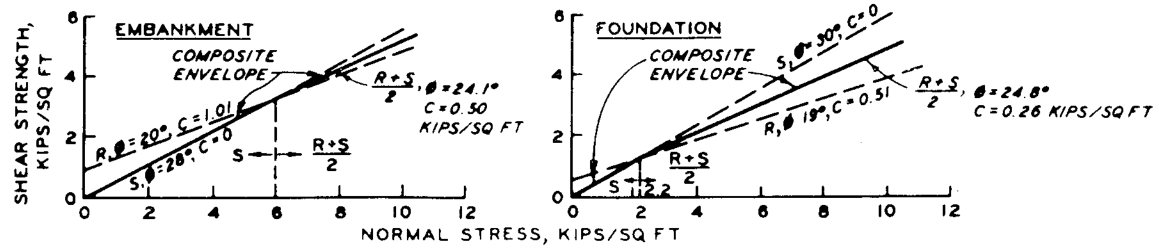


FIGURE 2. COMPOSITE STRENGTH ENVELOPES

ADOPTED DESIGN DATA								
MATERIAL	TAN ϕ: R	TAN ϕ: S	TAN ϕ: $\frac{R+S}{2}$	COHESION KIPS/SQ FT: R	COHESION KIPS/SQ FT: S	COHESION KIPS/SQ FT: $\frac{R+S}{2}$	UNIT WT LB/CU FT: γ_m	UNIT WT LB/CU FT: γ'
EMBANKMENT	0.364	0.532	0.448	1.01	0	0.50	130	68
FOUNDATION	0.344	0.577	0.461	0.51	0	0.26	–	63

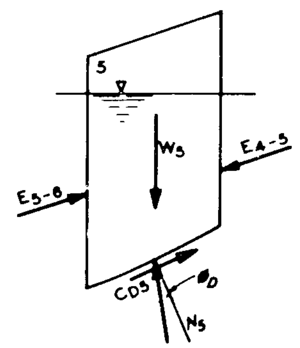


FIGURE 4. TYPICAL SLICE

NOTES FOR FIGURE 3:

THE SHEAR STRENGTH USED FOR EACH SLICE IN THE FORCE POLYGON IS SELECTED BY TRIAL. WHEN THE NORMAL FORCE N_D (DETERMINED USING THE S STRENGTH) DIVIDED BY THE BASE LENGTH OF THE SLICE EXCEEDS 6.0 KIPS/SQ FT IN THE EMBANKMENT OR 2.2 KIPS/SQ FT IN THE FOUNDATION, THE $\frac{R+S}{2}$ STRENGTH IS USED FOR THAT SLICE.

FOR TRIAL F. S. = 1.68:

	FOUNDATION: S_F	FOUNDATION: $\frac{R+S}{2}$	EMBANKMENT: S_E	EMBANKMENT: $\frac{R+S}{2}$
TAN Φ_D	0.344	0.274	0.317	0.266
Φ_D, DEG	18.9	15.3	17.6	14.9
C_D, KIPS/SQ FT	0	0.155	0	0.297

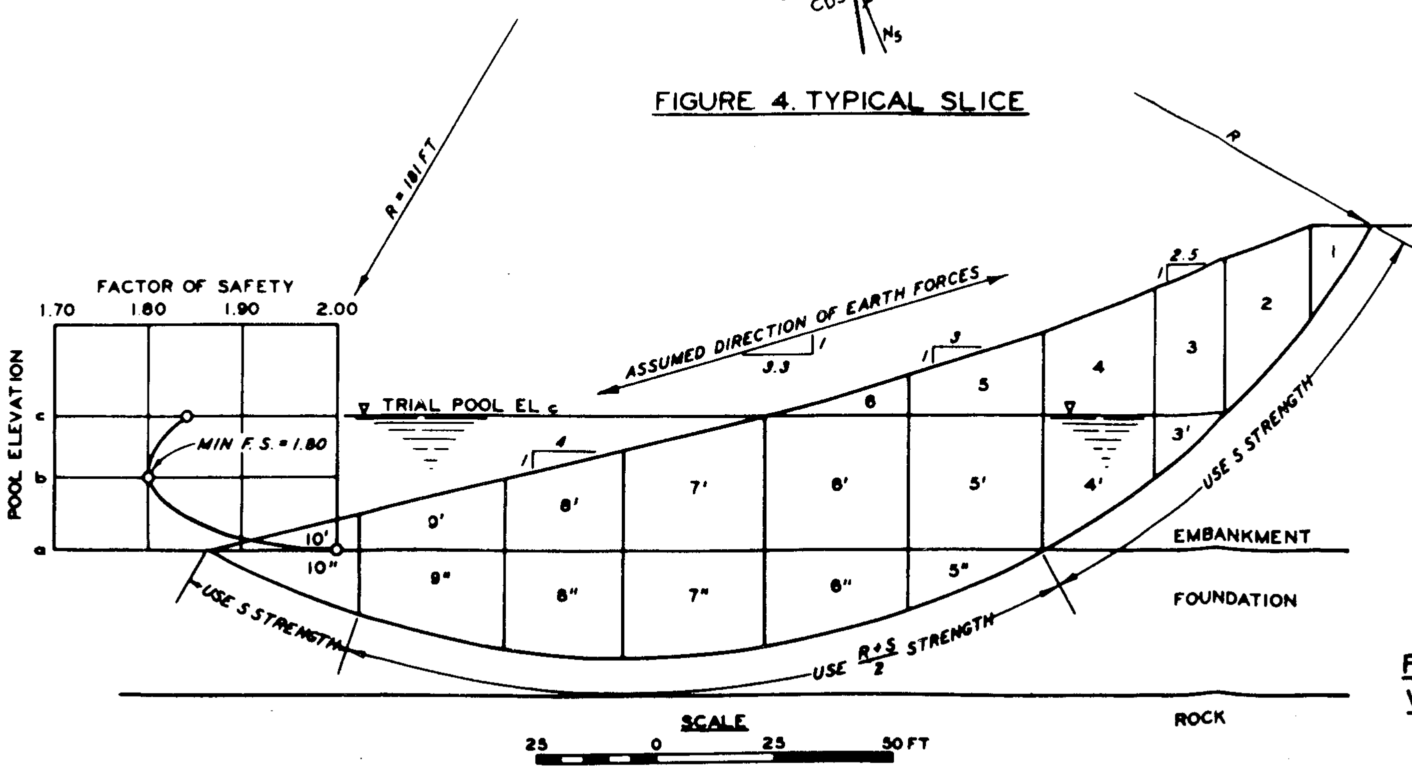


FIGURE 1. EMBANKMENT SECTION

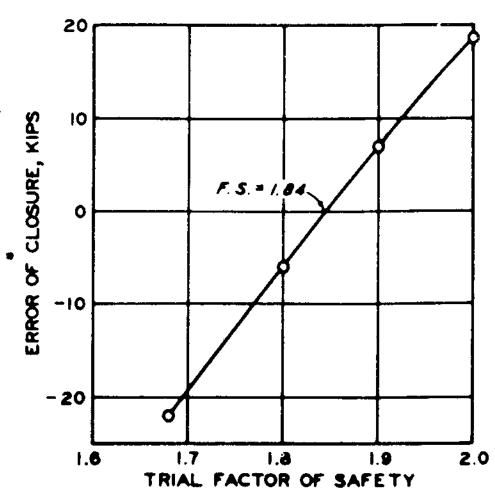


FIGURE 5. TRIAL FACTOR OF SAFETY VERSUS ERROR OF CLOSURE, POOL c

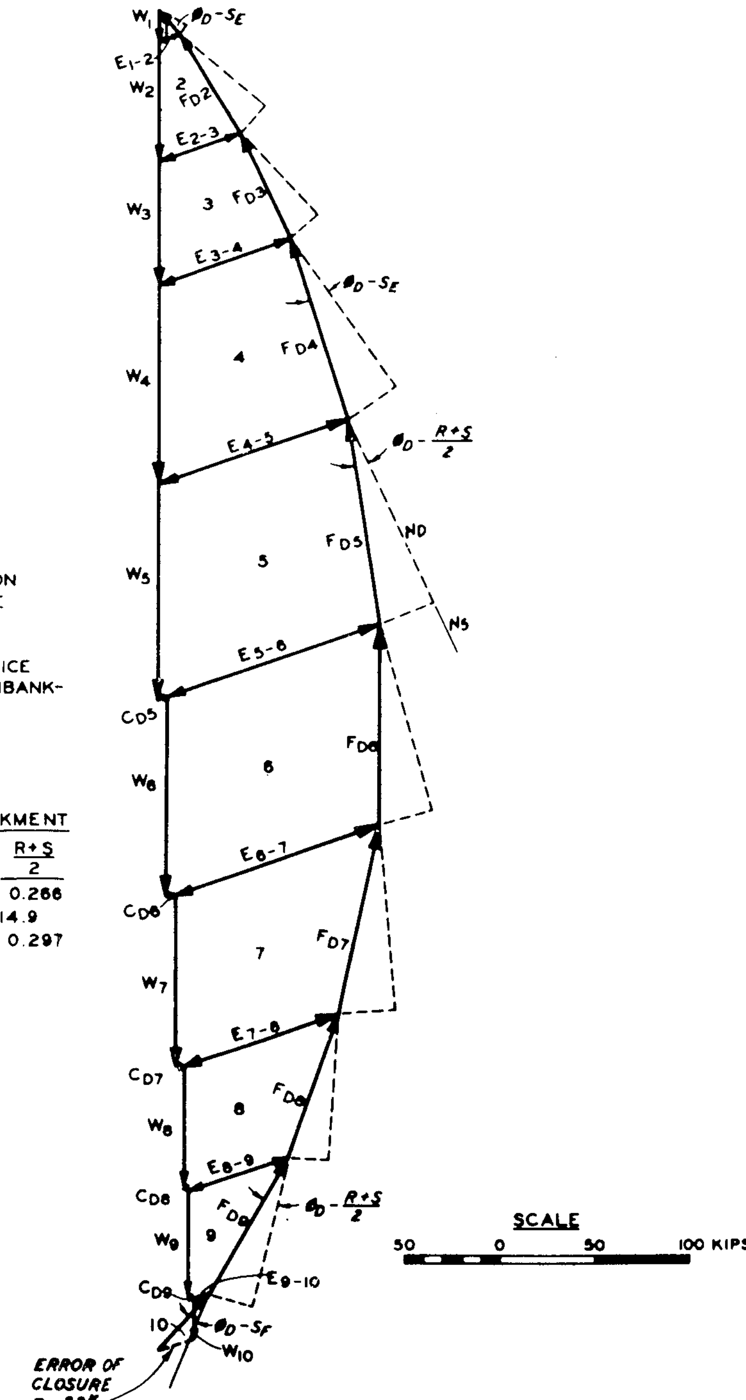


FIGURE 3. COMPOSITE FORCE POLYGON POOL EL c, TRIAL F. S. = 1.68

STABILITY ANALYSIS, CASE IV-PARTIAL POOL, UPSTREAM SLOPE, MODIFIED SWEDISH METHOD, FINITE SLICE PROCEDURE

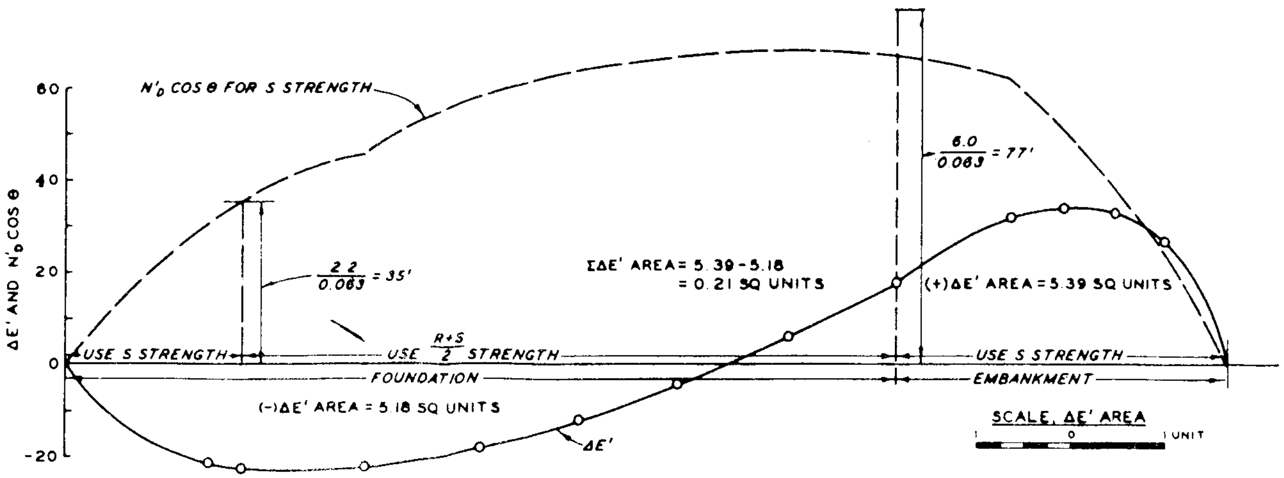


FIGURE 2. ΔE' AREA DIAGRAM AND N'_D COS θ DIAGRAM
TRIAL F. S. = 1.80, POOL EL b

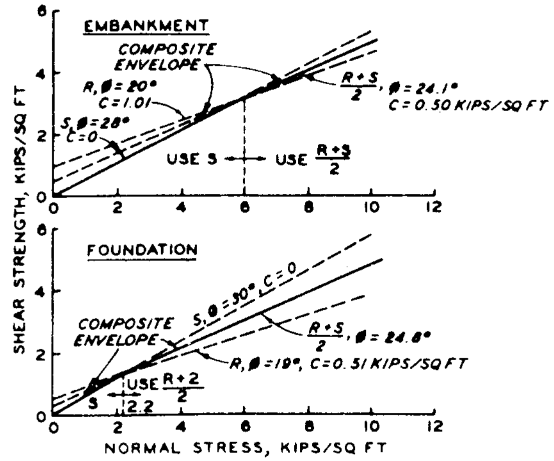


FIGURE 3. COMPOSITE STRENGTH ENVELOPES

ADOPTED DESIGN DATA								
MATERIAL	TAN φ			COHESION KIPS/SQ FT			UNIT WEIGHT LB/CU FT	
	R	S	(R + S)/2	R	S	(R + S)/2	γ_m	γ'
EMBANKMENT	0.364	0.532	0.448	1.01	0	0.50	130	68
FOUNDATION	0.344	0.577	0.461	0.51	0	0.26	—	63

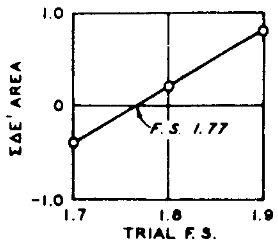


FIGURE 4. TRIAL FACTOR OF SAFETY VERSUS ΣΔE'
POOL EL b

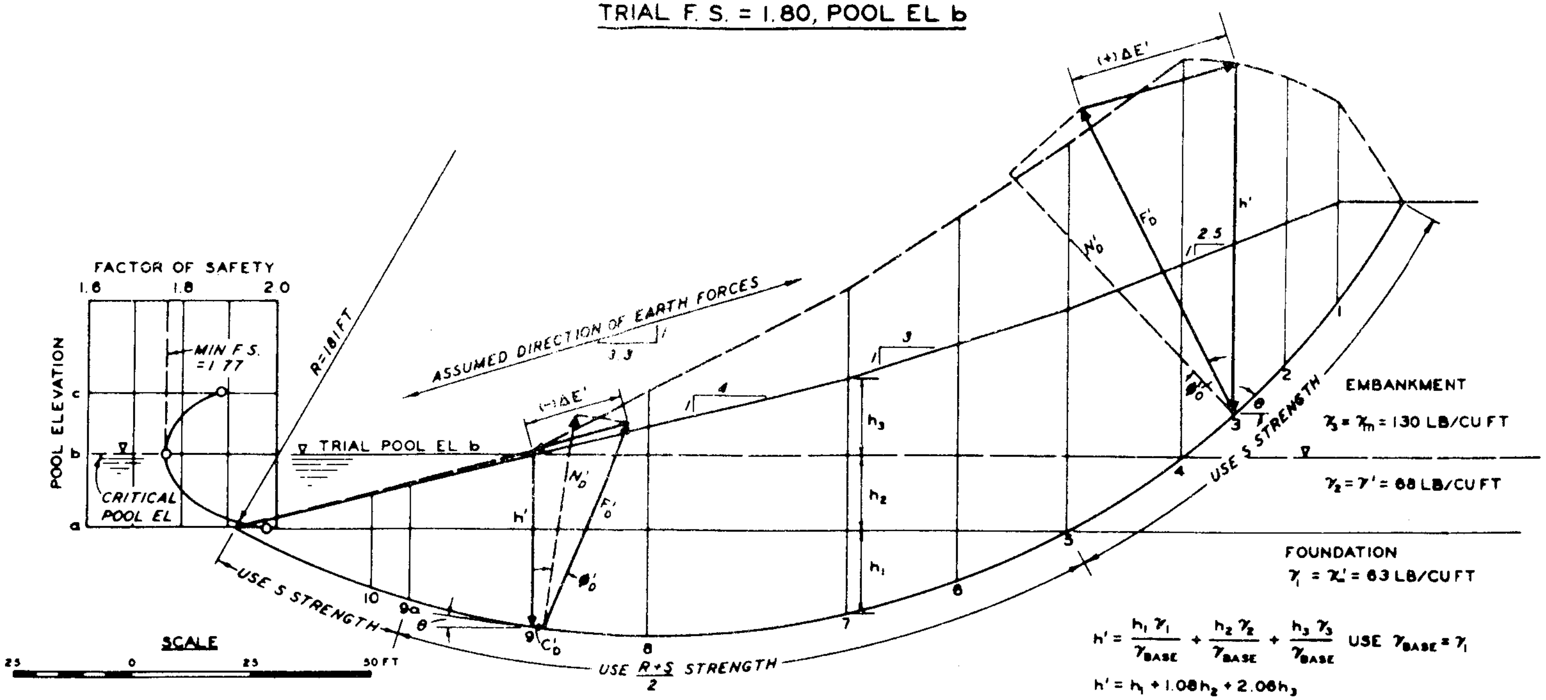


FIGURE 1. EMBANKMENT SECTION AND UNIT WIDTH SLICE
FORCE POLYGON, TRIAL F. S. = 1.80, POOL EL b

STABILITY ANALYSIS, CASE IV - PARTIAL POOL, UPSTREAM SLOPE, MODIFIED SWEDISH METHOD, GRAPHICAL INTEGRATION PROCEDURE

SLICE	HORIZONTAL WIDTH, FT	BASE LENGTH, ΔL FT	SLICE HEIGHT, FT: LEFT SIDE	SLICE HEIGHT, FT: RIGHT SIDE	SLICE HEIGHT, FT: AVERAGE	AREA OF SLICE, SQ FT	WEIGHT, KIPS: MOIST OR SATURATED WT	WEIGHT, KIPS: SUBMERGED WT	WEIGHT, KIPS: TOTAL WT	PIEZOMETRIC HEIGHT AT BASE OF SLICE, FT: LEFT	PIEZOMETRIC HEIGHT AT BASE OF SLICE, FT: RIGHT	WATER PRESSURE ON BASE KIPS/SQ FT: LEFT	WATER PRESSURE ON BASE KIPS/SQ FT: RIGHT	U_L, KIPS	U_R, KIPS	$(U_L - U_R)$, KIPS	UPLIFT U_B, KIPS
1	30.5	51.0	0	53.0	26.5	808	105	—	105	0	25	0	1.6	0	20.0	-20.0	40.8
2	20.5	29.0	53.0	73.5	63.2	1296	169	—	169	25	39	1.6	2.4	20.0	46.8	-26.8	58.0
3	56.3	69.0	73.5	89.5	81.5	4588	595	—	595	39	44	2.4	2.8	46.8	61.6	-14.8	179.4
4 4''	21.5	23.5	89.5 0	81.5 9.8	85.5 4.9	1838 105	239 13	— —	252	44	32	2.8	2.0	61.6	32.0	+29.6	56.4
5 5' 5''	35.0	37.5	59.0 22.5 9.8	45.5 22.5 22.0	52.3 22.5 15.9	1831 788 556	238 — —	— 53 35	326	—	—	—	—	—	—	—	—
6 6' 6''	35.0	35.5	45.5 22.5 22.0	34.0 22.5 29.8	39.8 22.5 25.9	1393 788 907	181 — —	— 53 57	291	—	—	—	—	—	—	—	—
7 7' 7''	39.0	39.4	34.0 22.5 29.8	21.0 22.5 32.5	27.5 22.5 31.2	1073 878 1217	139 — —	— 59 76	274	—	—	—	—	—	—	—	—
8 8' 8''	63.0	63.5	21.0 22.5 32.5	0 22.5 24.5	10.5 22.5 28.5	661 1417 1796	86 — —	— 96 112	294	—	—	—	—	—	—	—	—
9' 9''	67.0	—	22.5 24.5	0 0	11.3 12.3	757 824	— —	51 52	103								

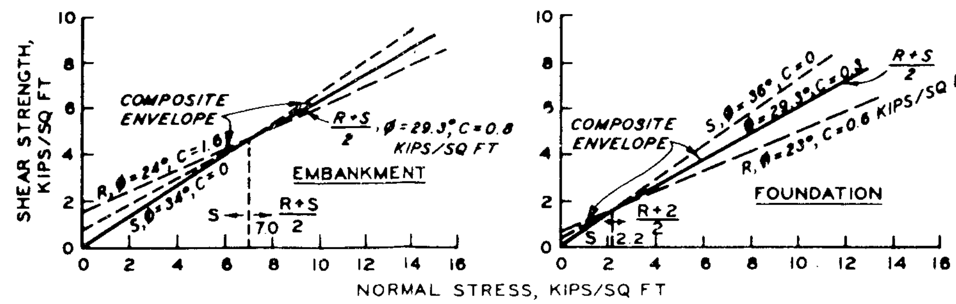
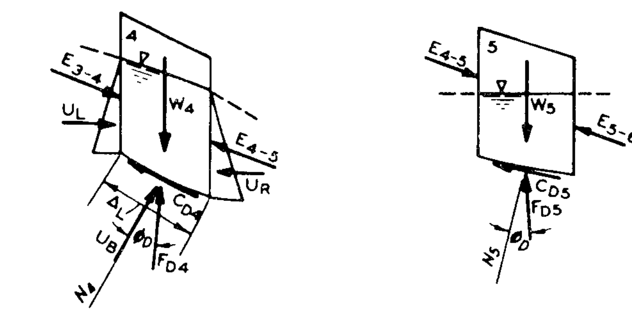


FIGURE 2. COMPOSITE STRENGTH ENVELOPES

ADOPTED DESIGN DATA								
MATERIAL	TAN φ			COHESION KIPS/SQ FT			UNIT WT LB/CU FT	
	R	S	$\frac{R+S}{2}$	R	S	$\frac{R+S}{2}$	γ_m	γ'
EMBANKMENT	0.455	0.675	0.560	1.6	0	0.8	130	67.5
FOUNDATION	0.424	0.700	0.562	0.6	0	0.3	125	62.5



a. SLOPING WATER SURFACE (SLICES 1-4). TOTAL WEIGHTS USED

b. HORIZONTAL WATER SURFACE (SLICES 5-9). SUBMERGED WEIGHTS USED BELOW WATER SURFACE

FIGURE. 3 TYPICAL SLICES

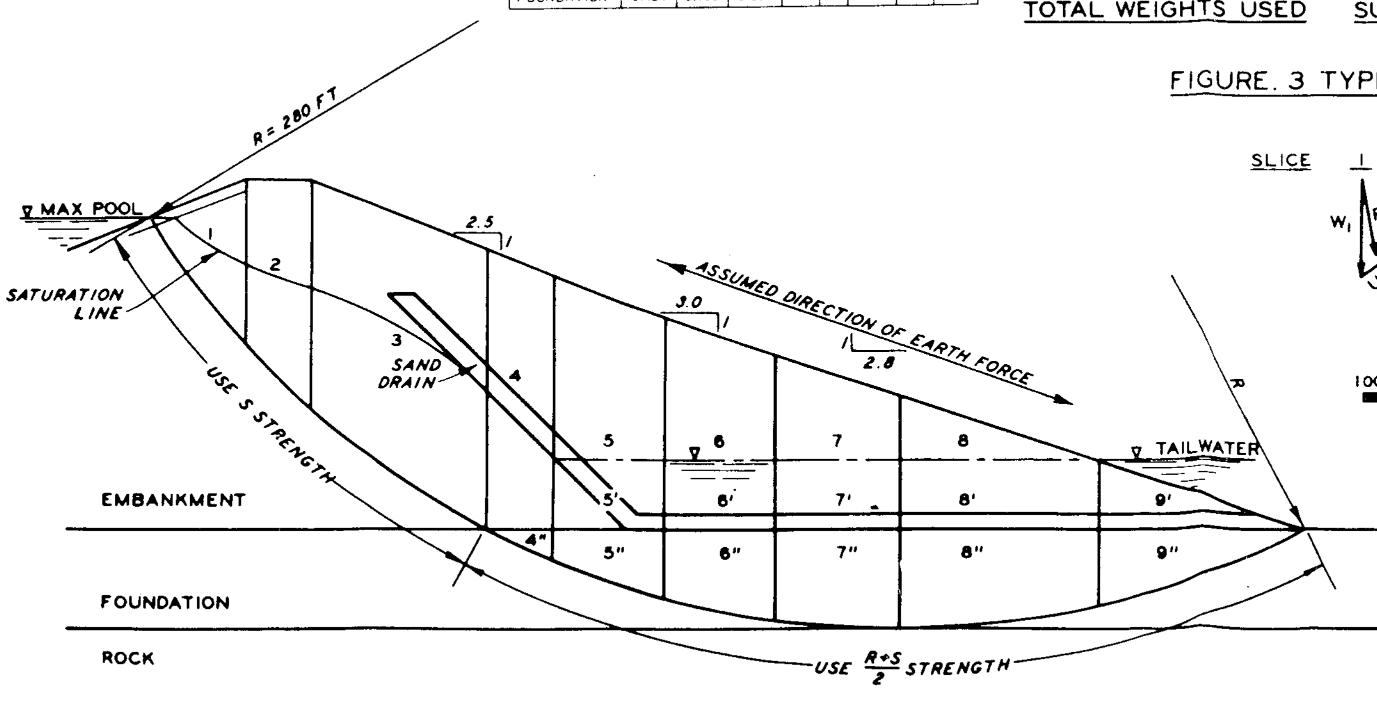


FIGURE 1. EMBANKMENT SECTION

SCALE
25 0 25 50 FT

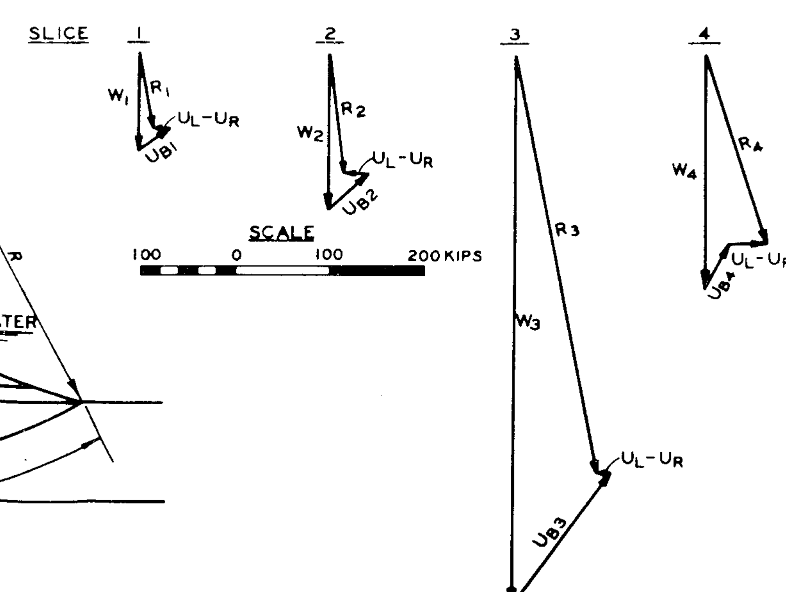


FIGURE 4. RESULTANTS OF WEIGHT AND WATER FORCES ON SLICE

NOTES FOR FIGURE 5:

THE SHEAR STRENGTH USED FOR EACH SLICE IN THE FORCE POLYGON IS SELECTED BY TRIAL. WHEN THE NORMAL FORCE N_D (DETERMINED USING THE S STRENGTH) DIVIDED BY THE BASE LENGTH OF THE SLICE EXCEEDS 7.0 KIPS/SQ FT IN THE EMBANKMENT OR 2.2 KIPS/SQ FT IN THE FOUNDATION, THE $\frac{R+S}{2}$ STRENGTH IS USED FOR THAT SLICE.

FOR TRIAL F. S. = 1.80:

	FOUNDATION: S	FOUNDATION: $\frac{R+S}{2}$	EMBANKMENT: S	EMBANKMENT: $\frac{R+S}{2}$
TAN Φ_D	0.375	0.311	0.389	0.312
Φ_D, DEG	20.6	17.3	21.3	17.4
C_D, KIPS/SQ FT	0	0.167	0	0.444

SCALE
200 0 200 400 KIPS

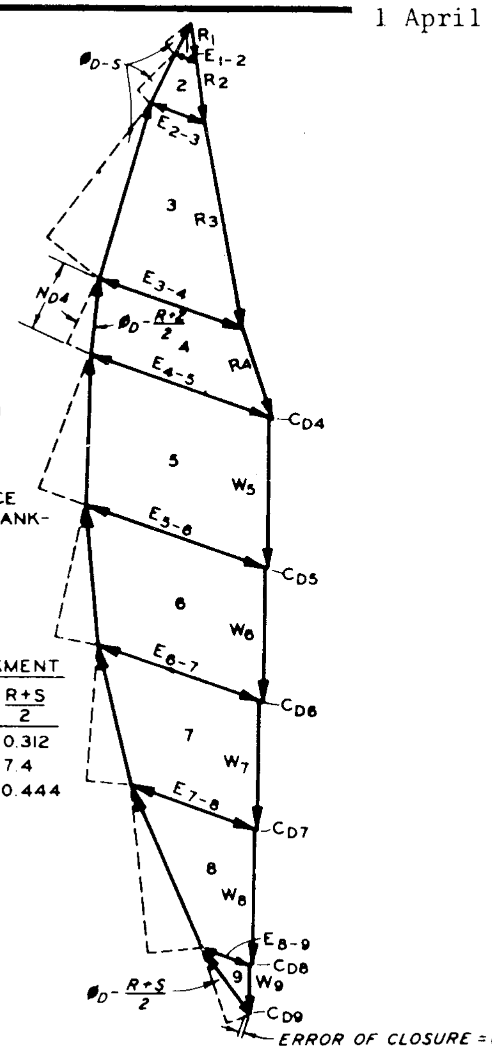


FIGURE 5. COMPOSITE FORCE POLYGON FOR TRIAL F. S. = 1.80

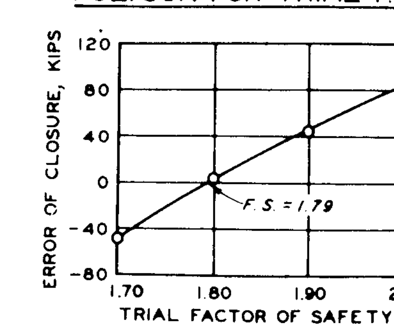


FIGURE 6. TRIAL FACTOR OF SAFETY VERSUS ERROR OF CLOSURE

STABILITY ANALYSIS, CASE V - STEADY SEEPAGE, DOWNSTREAM SLOPE, MAX STORAGE POOL, MODIFIED SWEDISH METHOD, FINITE SLICE PROCEDURE

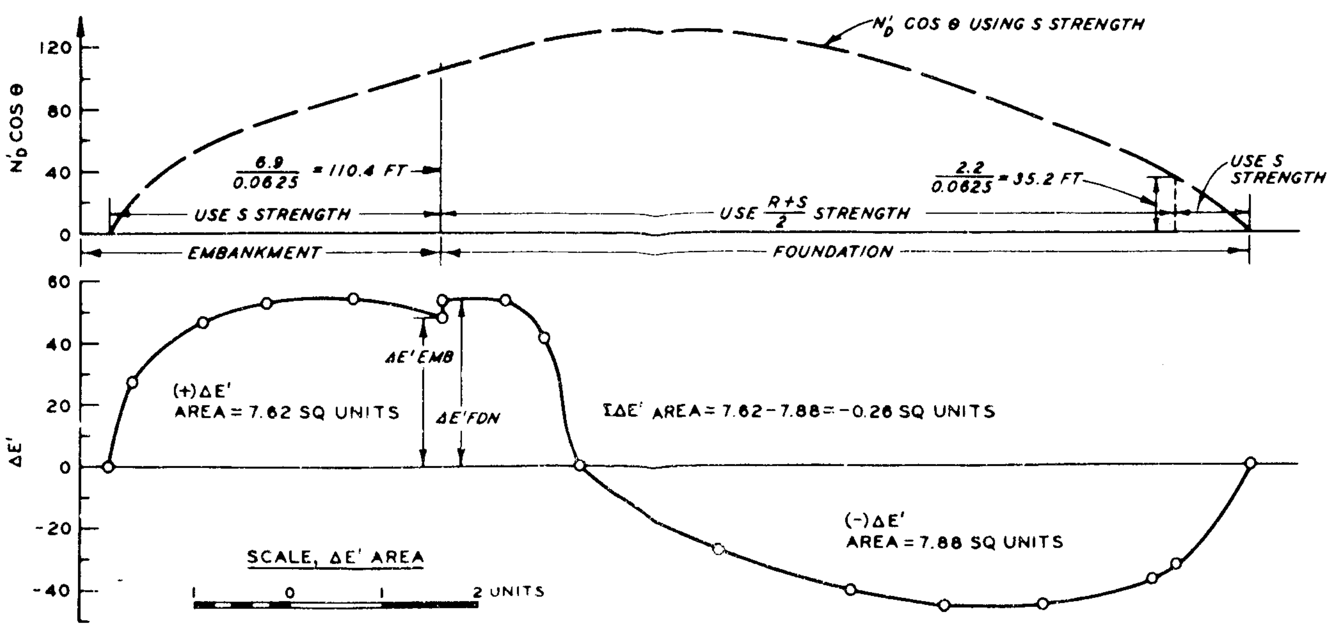


FIGURE 2. ΔE' AREA DIAGRAM AND N'_D COS θ DIAGRAM, TRIAL F.S. = 1.80

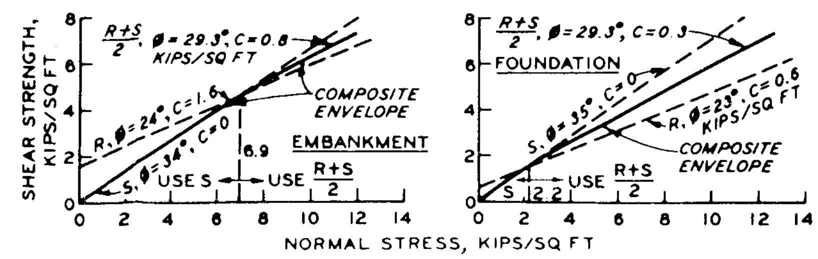


FIGURE 3. COMPOSITE STRENGTH ENVELOPES

ADOPTED DESIGN DATA							
MATERIAL	TAN φ			COHESION KIPS/SQ FT			UNIT WT LB/CU FT
	R	S	$\frac{R+S}{2}$	R	S	$\frac{R+S}{2}$	γ_m
EMBANKMENT	0.445	0.675	0.560	1.6	0	0.8	130
FOUNDATION	0.424	0.700	0.562	0.6	0	0.3	125

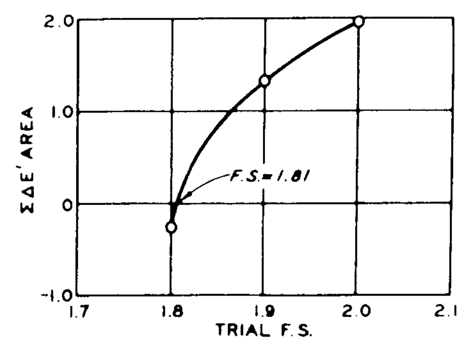


FIGURE 4. TRIAL F.S. VERSUS ΣΔE

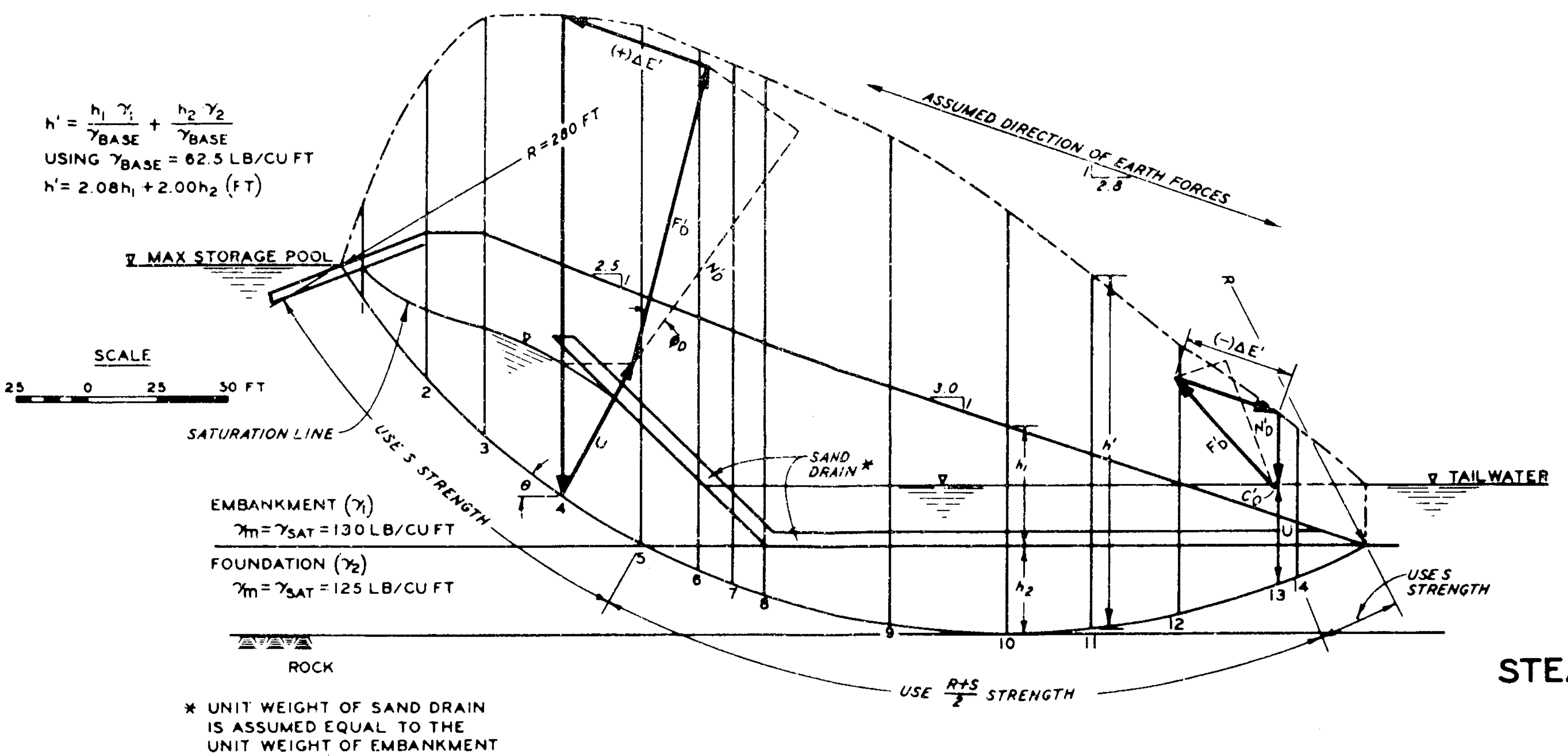


FIGURE 1. EMBANKMENT SECTION AND UNIT WIDTH SLICE FORCE POLYGONS, TRIAL F.S. = 1.8

STABILITY ANALYSIS, CASE V – STEADY SEEPAGE, DOWNSTREAM SLOPE, MAX STORAGE POOL, MODIFIED SWEDISH METHOD, GRAPHICAL INTEGRATION PROCEDURE

SLICE	HORIZONTAL WIDTH, FT	BASE LENGTH, ΔL FT	SLICE HEIGHT, FT			AREA OF SLICE SQ FT	WEIGHT, KIPS				EARTHQUAKE FORCE, F_h, KIPS	PIEZOMETRIC HEIGHT AT BASE OF SLICE, FT		WATER PRESSURE ON BASE KIPS SQ FT		U_L, KIPS	U_R, KIPS	$(U_L - U_R)$, KIPS	UPLIFT U_B, KIPS
			LEFT SIDE	RIGHT SIDE	AVERAGE		MOIST OR SATURATED WT	SUBMERGED WT	EFFECTIVE TOTAL WT	TOTAL WT FOR EARTHQUAKE		LEFT	RIGHT	LEFT	RIGHT				
1	30.5	51.0	0	53.0	26.5	800	106	—	106	106	15.8	0	25	0	1.6	0	20.0	−20.0	40.8
2	20.5	29.0	53.0	73.5	63.2	1296	169	—	169	169	25.4	25	39	1.6	2.4	20.0	46.2	−26.2	58.0
3	56.3	69.0	73.5	89.5	81.5	4588	595	—	595	595	89.4	39	44	2.4	2.8	46.2	61.6	−14.4	179.4
4 4"	21.5	23.5	89.5 0	81.5 9.8	85.5 4.9	1838 106	239 13	—	252	252	37.8	44	32	2.8	2.0	61.6	32.0	+29.6	56.4
5 5' 5"	35.0	37.5	59.0 22.5 9.8	45.5 22.5 22.0	52.3 22.5 15.9	1831 788 556	238	53 35	326	410	61.5	—	—	—	—	—	—	—	—
6 6' 6"	35.0	35.5	45.5 22.5 22.0	34.0 27.5 29.8	39.8 22.5 25.9	1393 788 907	181	53 57	291	397	59.6	—	—	—	—	—	—	—	—
7 7' 7"	39.0	39.4	34.0 22.5 29.8	21.0 22.5 32.5	27.5 22.5 31.2	1073 878 1217	139	59 76	274	406	60.9	—	—	—	—	—	—	—	—
8 8' 8"	63.0	63.5	21.0 22.5 32.5	0 22.5 24.5	10.5 22.5 28.5	661 1417 1796	86	96 112	294	495	74.3	—	—	—	—	—	—	—	—
9' 9"	67.0	—	22.5 24.5	0 0	11.3 12.3	757 824	—	51 52	103	201	30.2	—	—	—	—	—	—	—	—

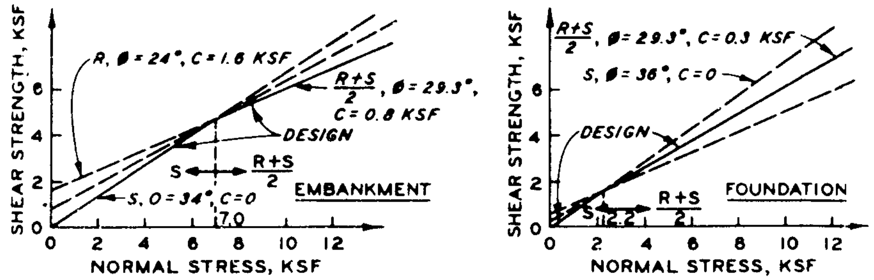
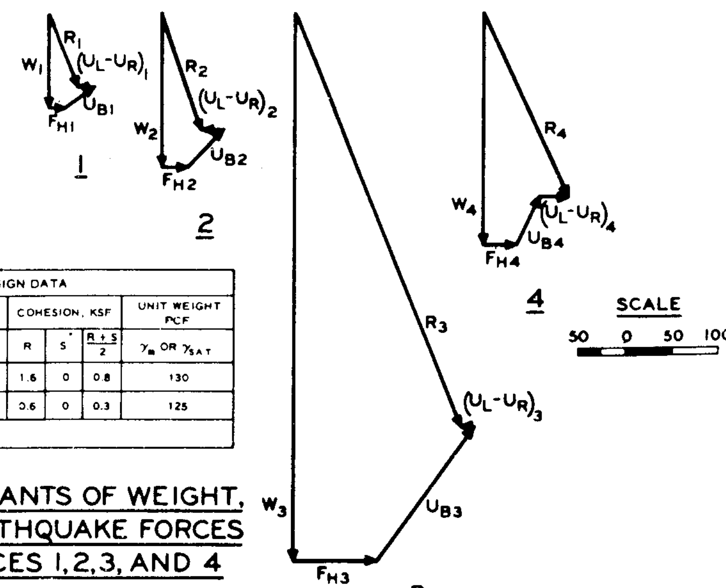
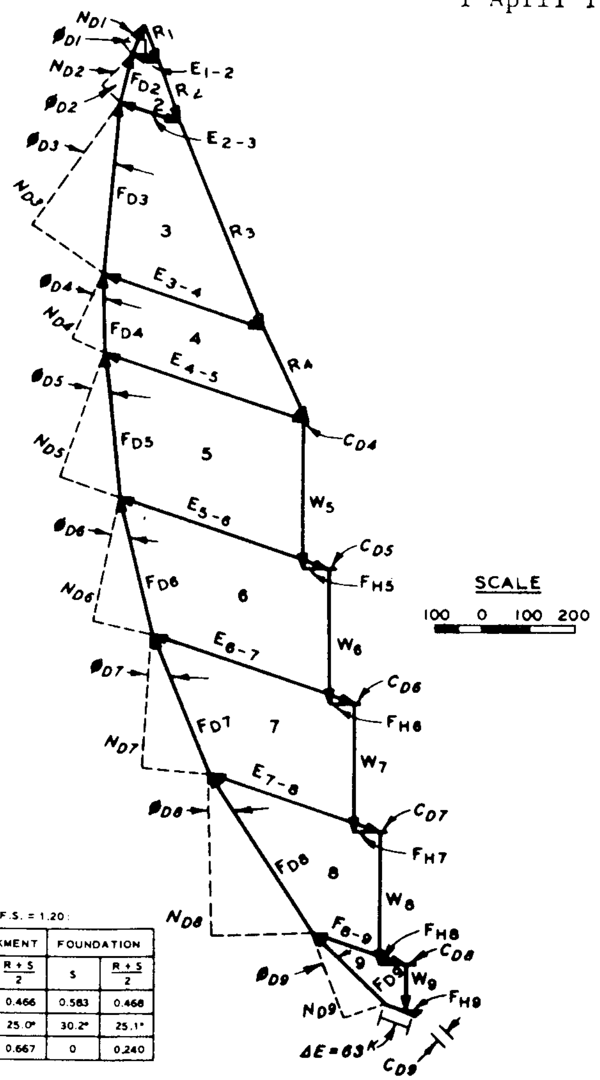


FIGURE 2. COMPOSITE STRENGTH ENVELOPES
(SAME AS IN PLATE VI-15)



ADOPTED DESIGN DATA							
MATERIAL	TAN ϕ			COHESION, KSF			UNIT WEIGHT PCF
	R	S	$\frac{R+S}{2}$	R	S	$\frac{R+S}{2}$	γ_m OR γ_{SAT}
EMBANKMENT	0.445	0.675	0.560	1.6	0	0.8	130
FOUNDATION	0.424	0.700	0.562	0.6	0	0.3	125
SEISMIC COEFFICIENT, ψ = 0.15							

FIGURE 3. RESULTANTS OF WEIGHT, WATER, AND EARTHQUAKE FORCES ACTING ON SLICES 1, 2, 3, AND 4



TRIAL F.S. = 1.20:

	EMBANKMENT		FOUNDATION	
	S	$\frac{R+S}{2}$	S	$\frac{R+S}{2}$
TAN ϕ_D	0.563	0.466	0.583	0.468
ϕ_D	29.4°	25.0°	30.2°	25.1°
C_D, KSF	0	0.667	0	0.240

FIGURE 4. COMPOSITE FORCE POLYGON FOR TRIAL F.S. = 1.20

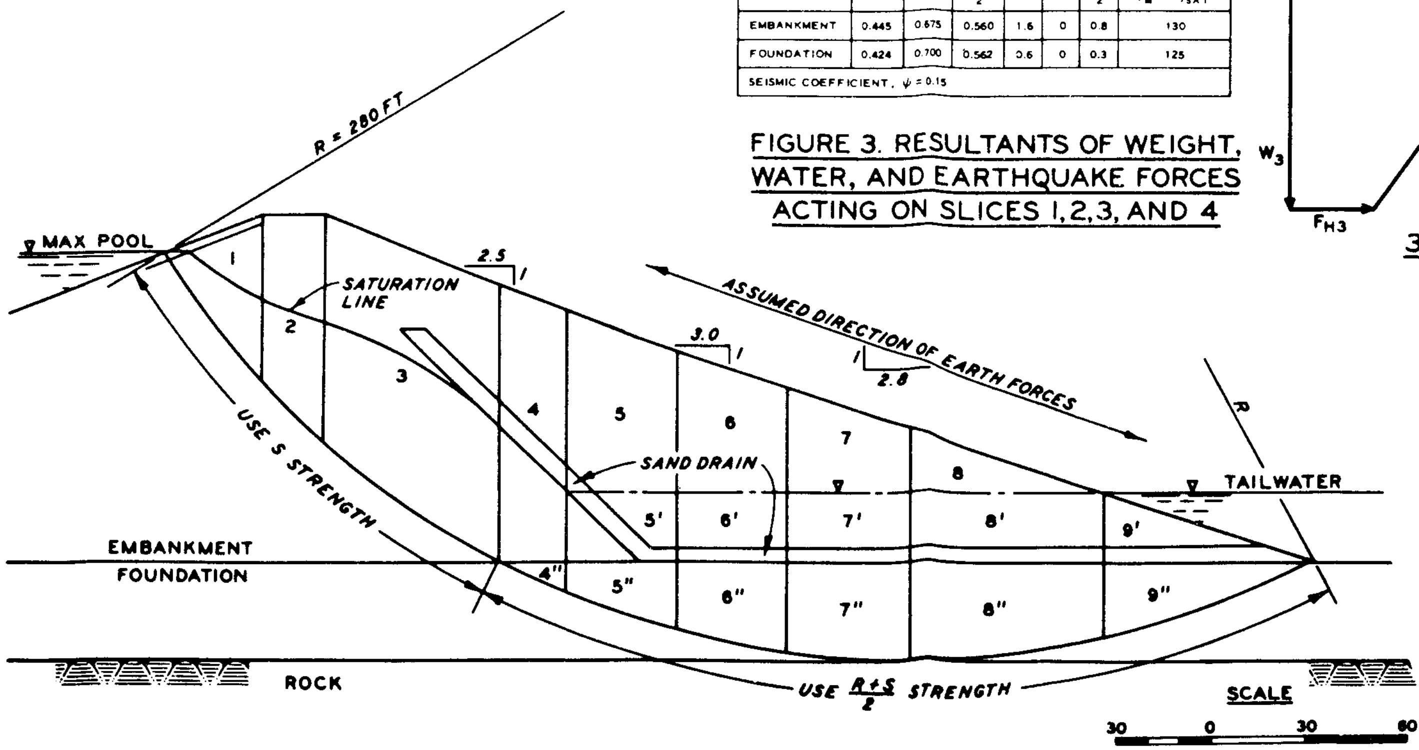


FIGURE 1. EMBANKMENT SECTION
(SAME AS IN PLATE VI-15)

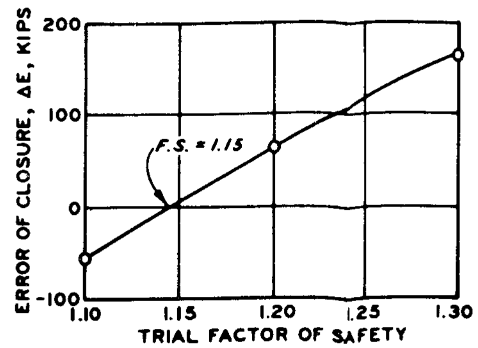


FIGURE 5. ERROR OF CLOSURE VS TRIAL FACTOR OF SAFETY

STABILITY ANALYSIS, CASE VII – EARTHQUAKE, STEADY SEEPAGE, DOWNSTREAM SLOPE, MODIFIED SWEDISH METHOD, FINITE SLICE PROCEDURE

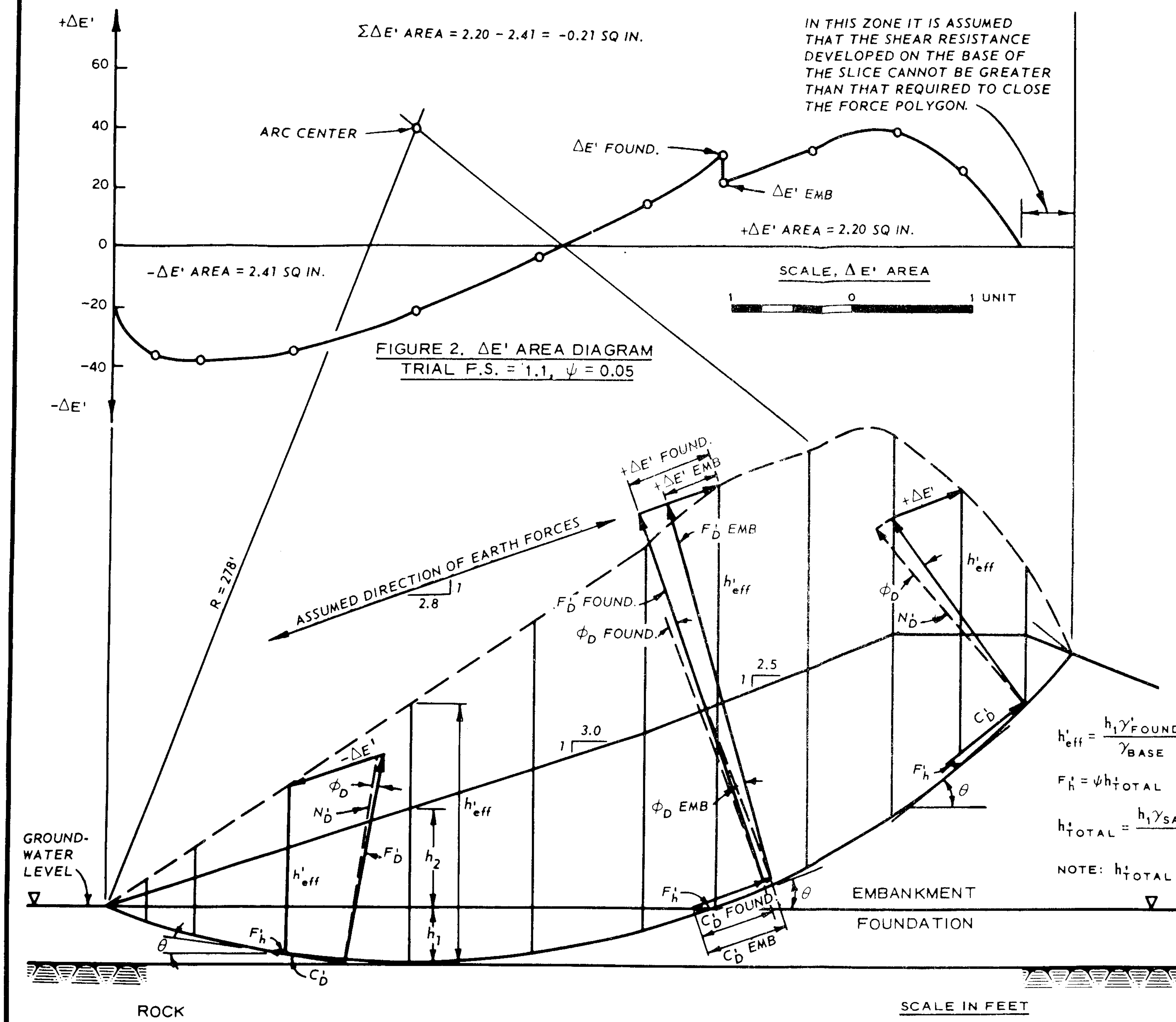


FIGURE 2. ΔE' AREA DIAGRAM
TRIAL F.S. = 1.1, ψ = 0.05

FIGURE 1. EMBANKMENT SECTION AND UNIT SLICE FORCE POLYGONS, TRIAL F.S. = 1.1, ψ = 0.05

ADOPTED DESIGN DATA							
MATERIAL	UNIT WEIGHT PCF			Q STRENGTH			ψ
	γ	γ_{SAT}	γ'	ϕ DEG	TAN ϕ	c KSF	
EMB	135	—	—	5	0.088	1.78	0.05
FOUND.	—	127.5	65.0	2	0.035	1.60	

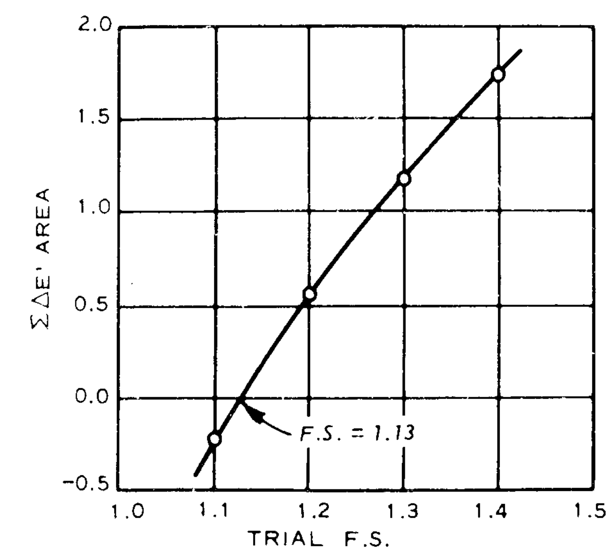


FIGURE 3. TRIAL F.S. VERSUS ΣΔE'

$h'_{eff} = \dfrac{h_1 \gamma'_{FOUND.}}{\gamma_{BASE}} + \dfrac{h_2 \gamma_{EMB}}{\gamma_{BASE}}$, USING $\gamma_{BASE} = \gamma'_{FOUND.} = 65$ PCF: $h'_{eff} = h_1 + 2.076\,h_2$

$F'_h = \psi h'_{TOTAL}$

$h'_{TOTAL} = \dfrac{h_1 \gamma_{SAT\,(FOUND.)}}{\gamma_{BASE}} + \dfrac{h_2 \gamma_{EMB}}{\gamma_{BASE}}$, USING $\gamma_{BASE} = \gamma'_{FOUND.} = 65$ PCF: $h'_{TOTAL} = 1.96\,h_1 + 2.076\,h_2$

NOTE: h'_{TOTAL} IS USED ONLY TO COMPUTE F'_h; h'_{eff} IS USED IN THE FORCE POLYGONS.

NOTE: EMBANKMENT SECTION AND ADOPTED DESIGN DATA ARE SAME AS IN PLATE VI-9.

STABILITY ANALYSIS, CASE VII - EARTHQUAKE, END OF CONSTRUCTION MODIFIED SWEDISH METHOD GRAPHICAL INTEGRATION PROCEDURE